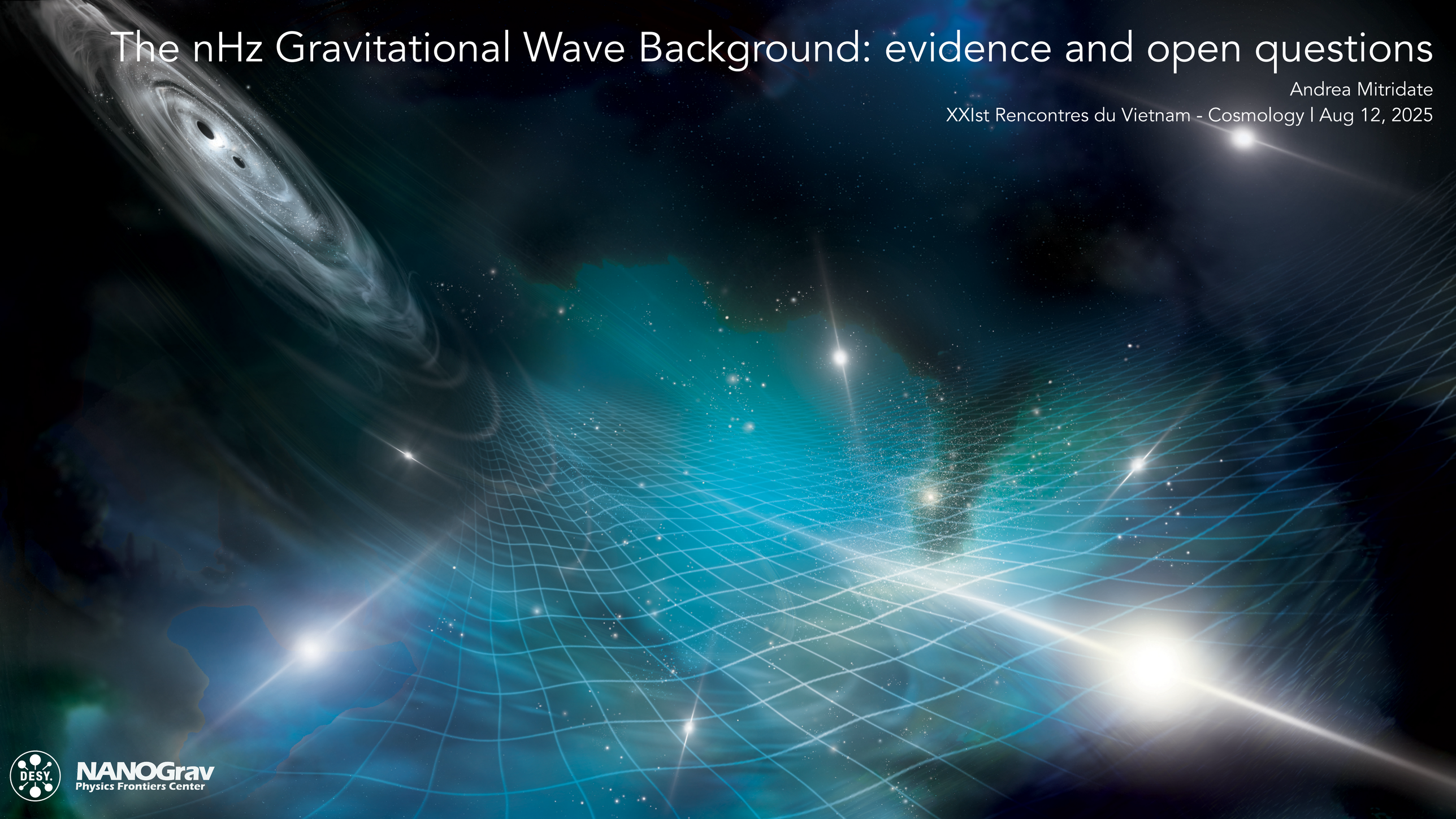
The nHz Gravitational Wave Background: evidence and open questions

Andrea Mitridate

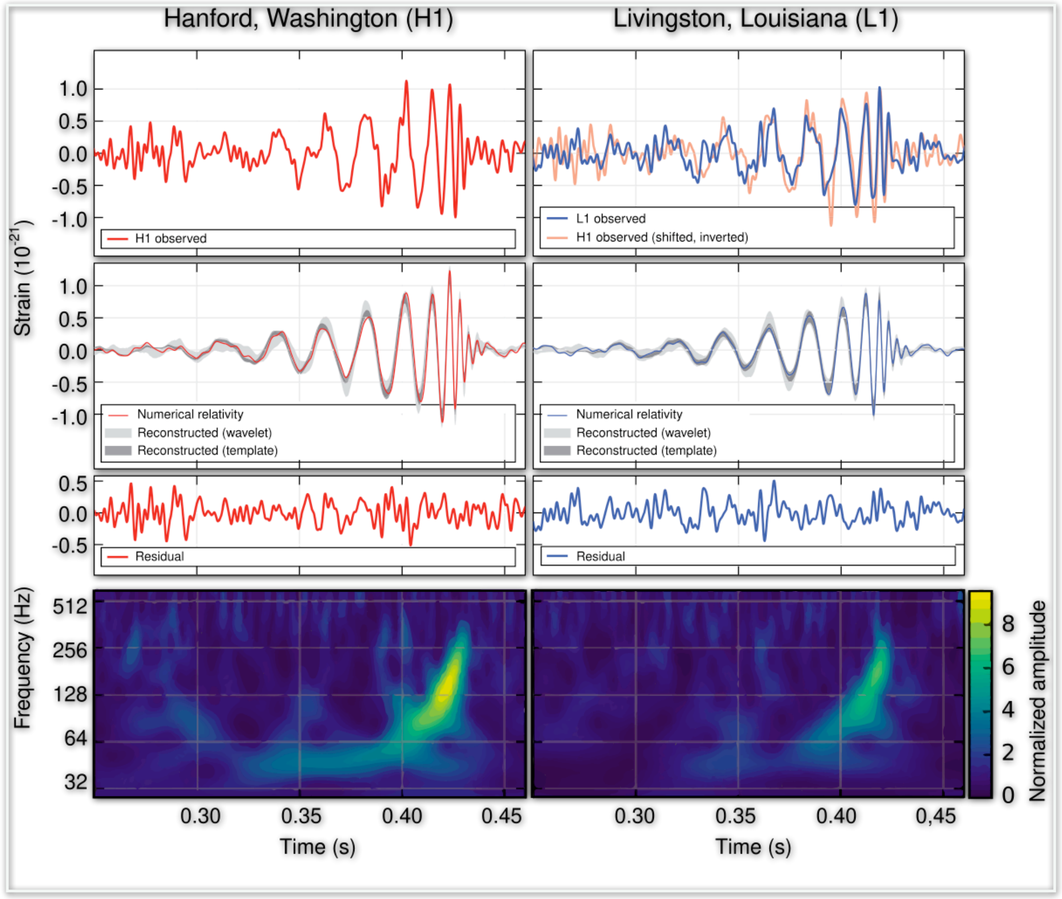
XXIst Rencontres du Vietnam - Cosmology I Aug 12, 2025



DESY.

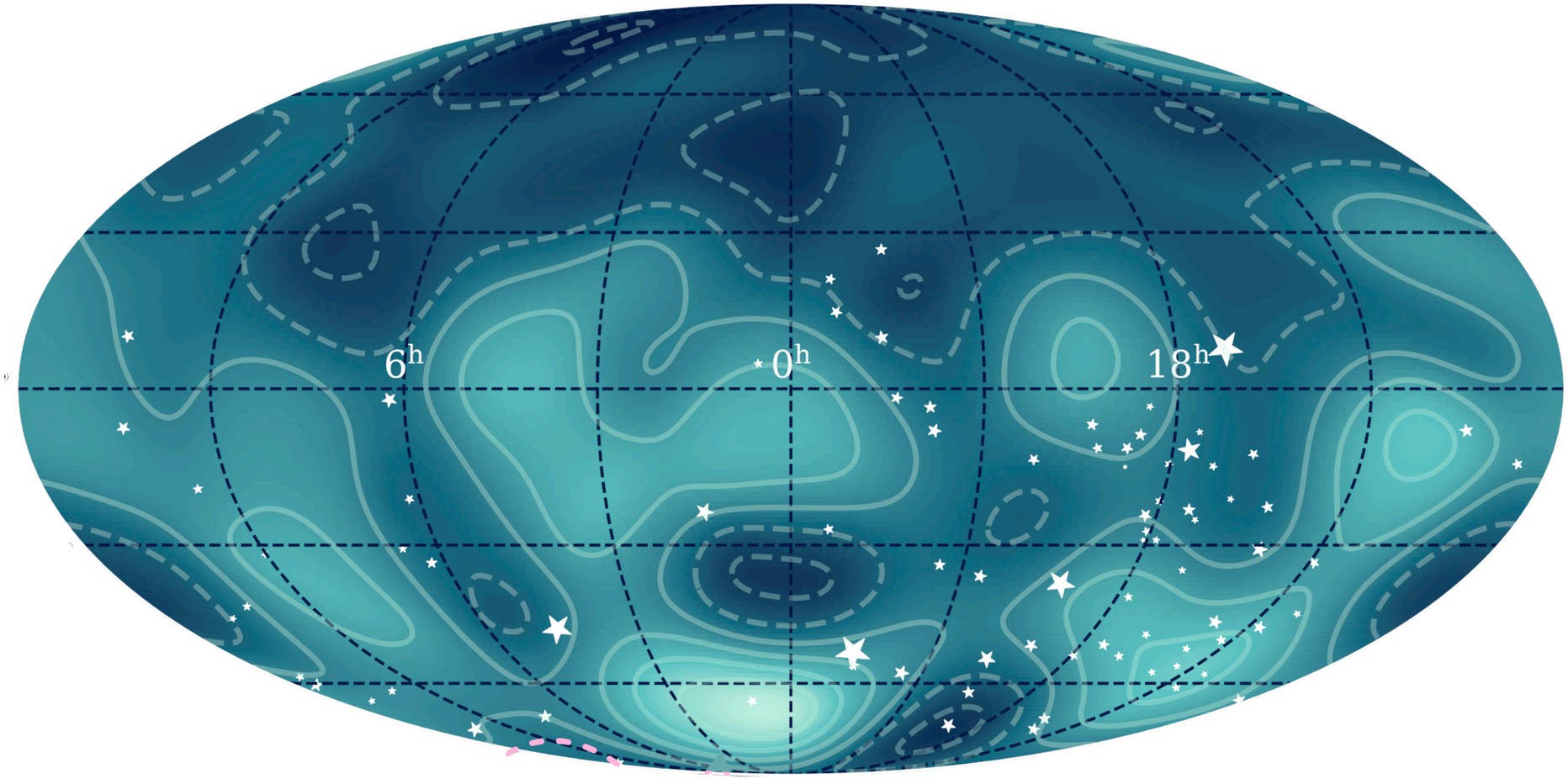
NANOGrav
Physics Frontiers Center

INITIAL DISCLAIMER



localized and **transient** events

INITIAL DISCLAIMER



persistent and **all-sky**

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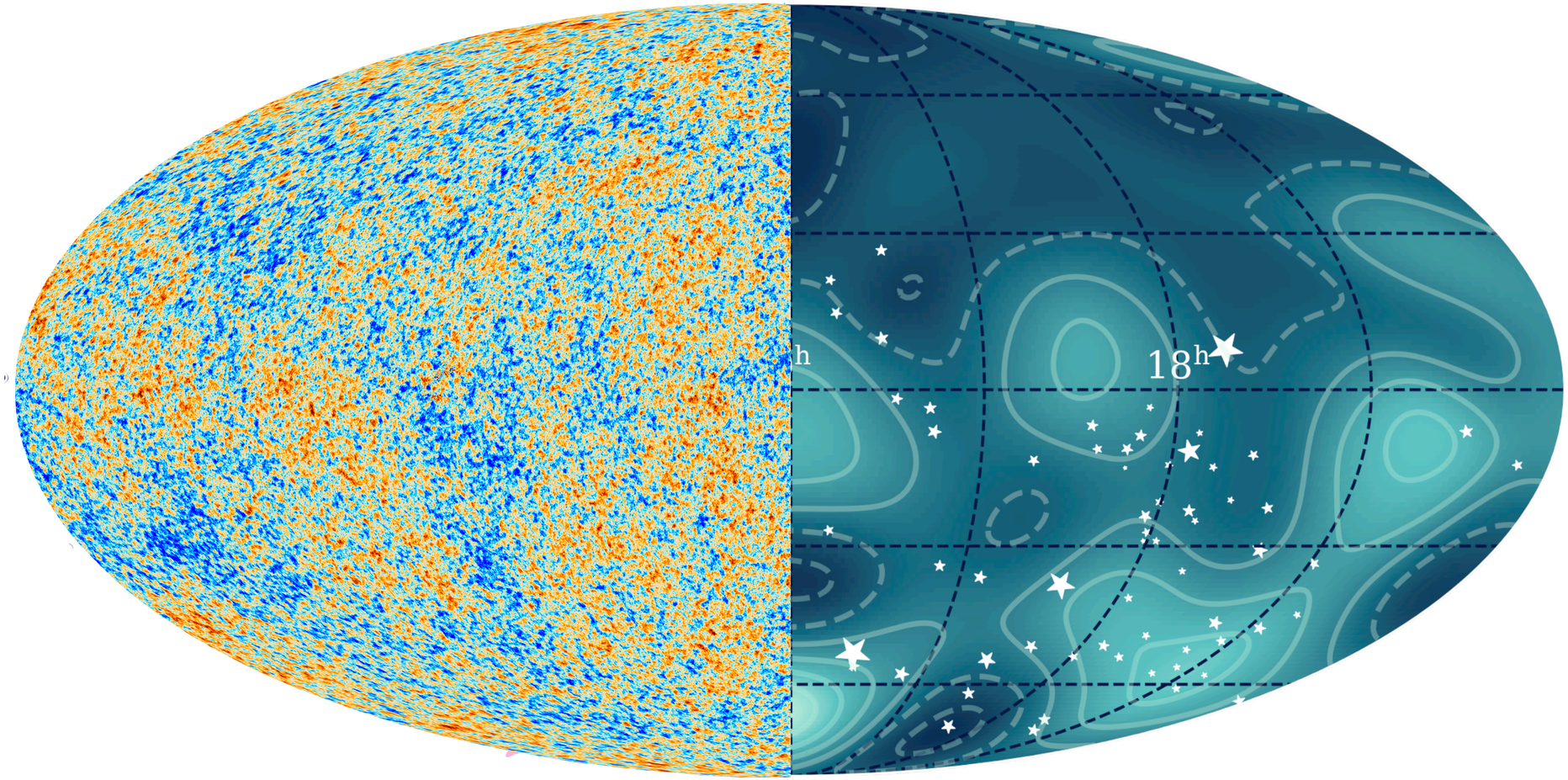
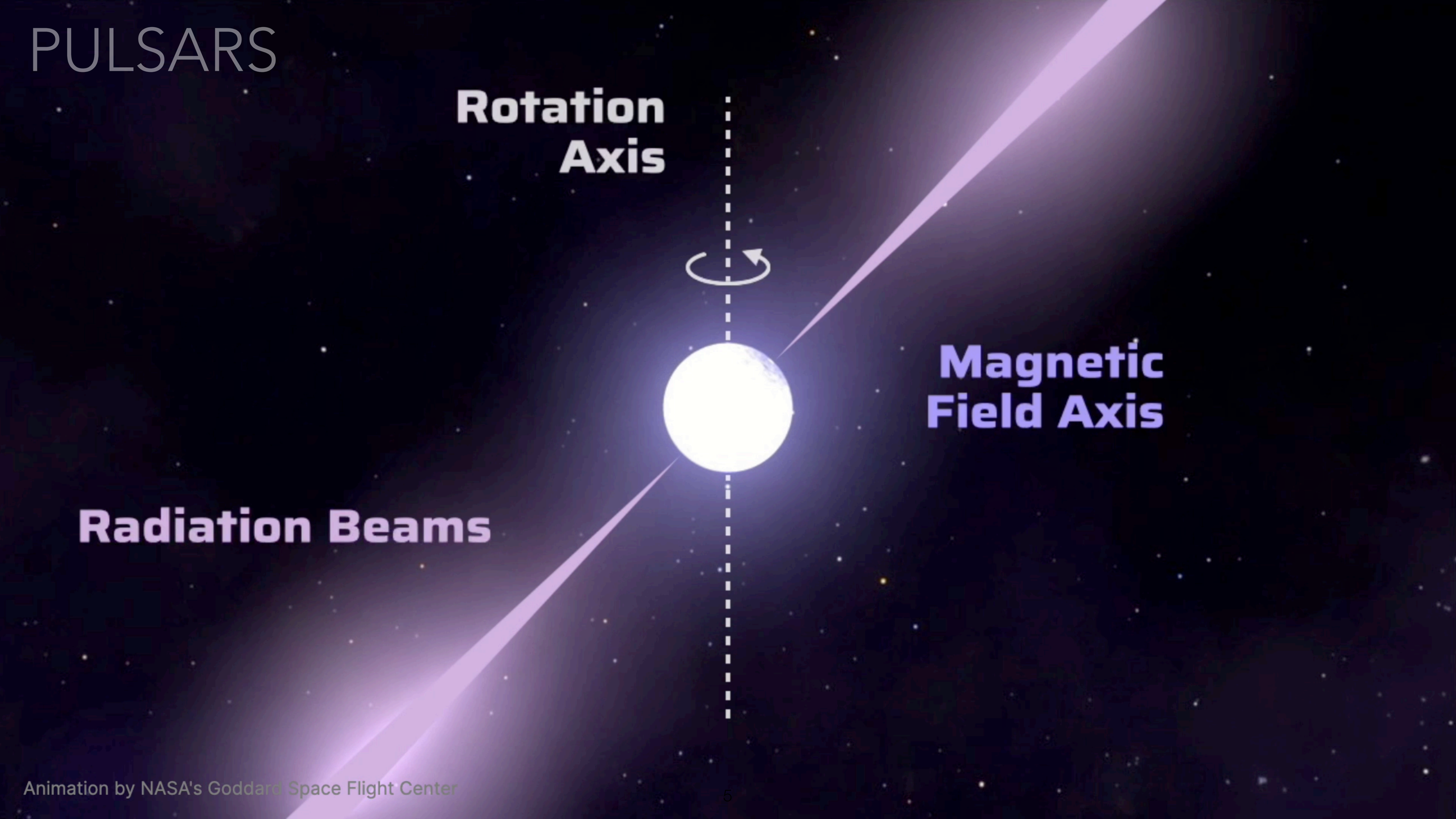


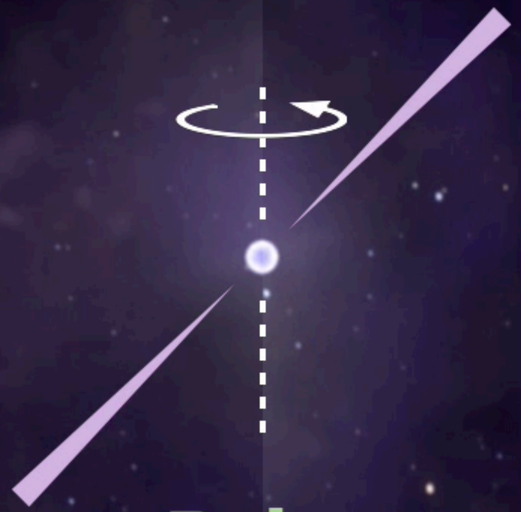
persistent and **all-sky**

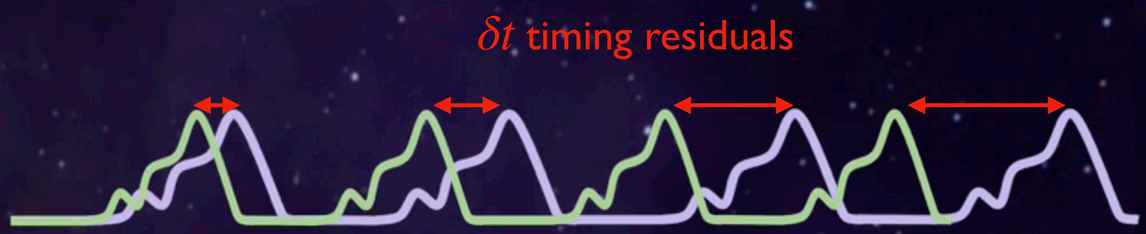
PULSARS



Animation by NASA's Goddard Space Flight Center

TIMING RESIDUALS





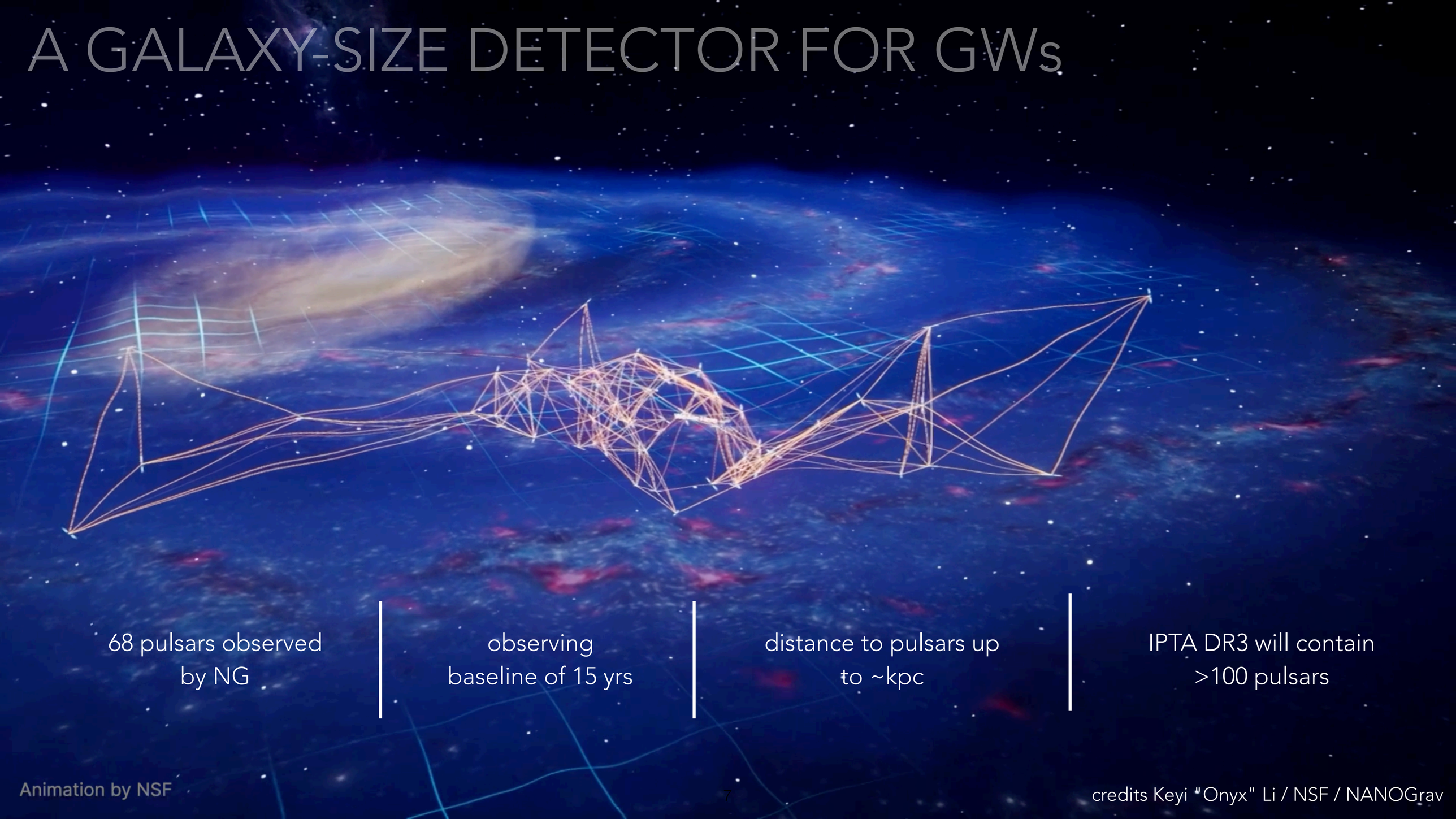
Pulses expected from Timing Model

Pulses Recorded by Radio Telescope

A GALAXY-SIZE DETECTOR FOR GWs

credits Keyi "Onyx" Li / NSF / NANOGrav

A GALAXY-SIZE DETECTOR FOR GWs



68 pulsars observed by NG

observing baseline of 15 yrs

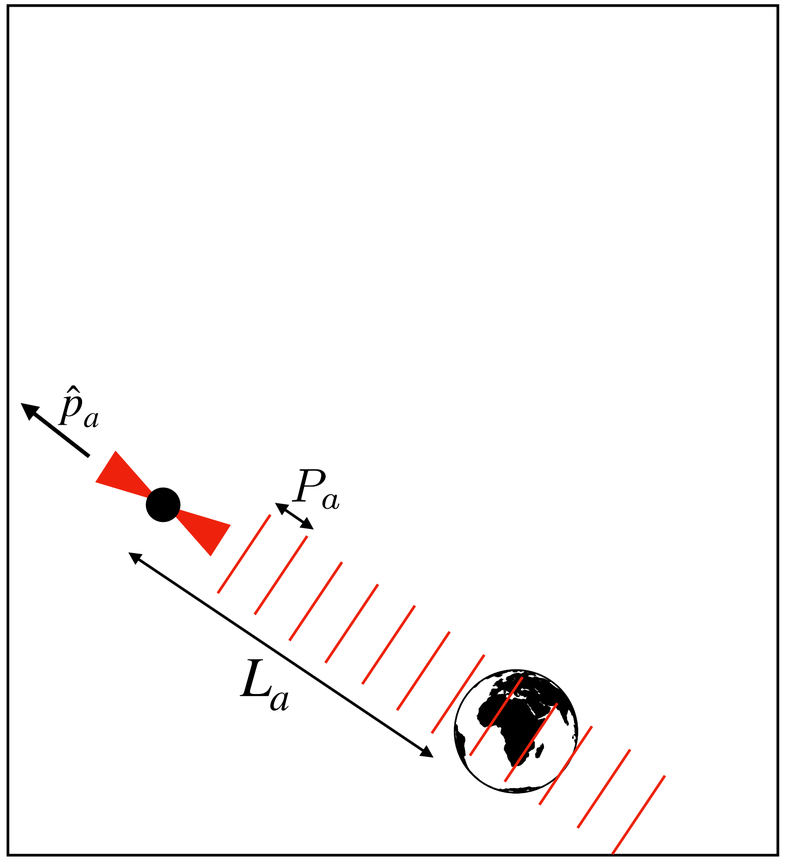
distance to pulsars up to ~kpc

IPTA DR3 will contain >100 pulsars

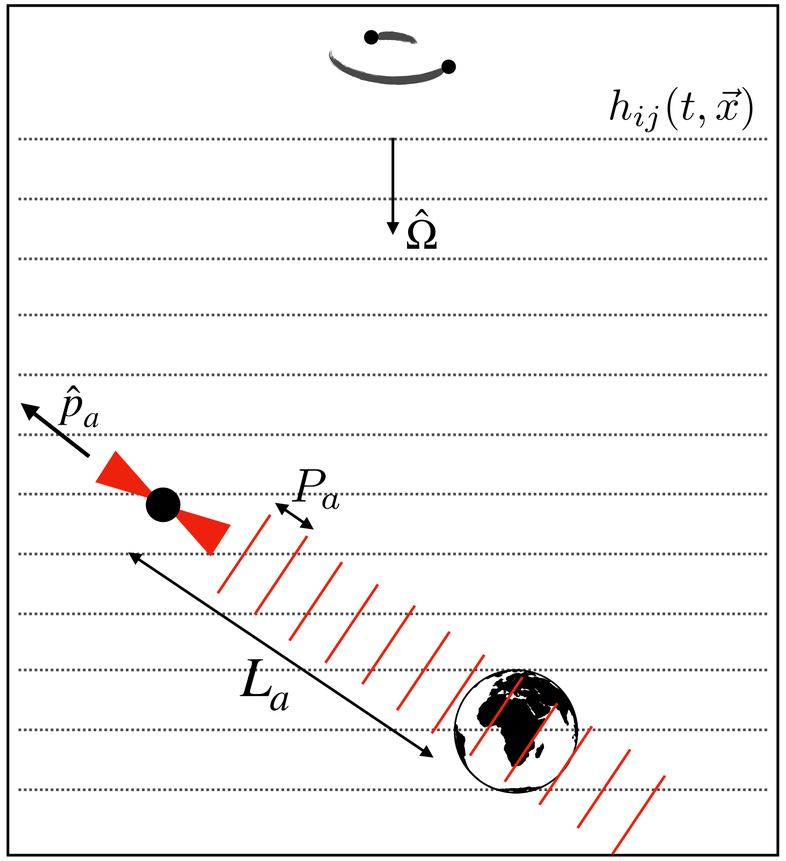
Animation by NSF

credits Keyi "Onyx" Li / NSF / NANOGrav

GW SIGNALS

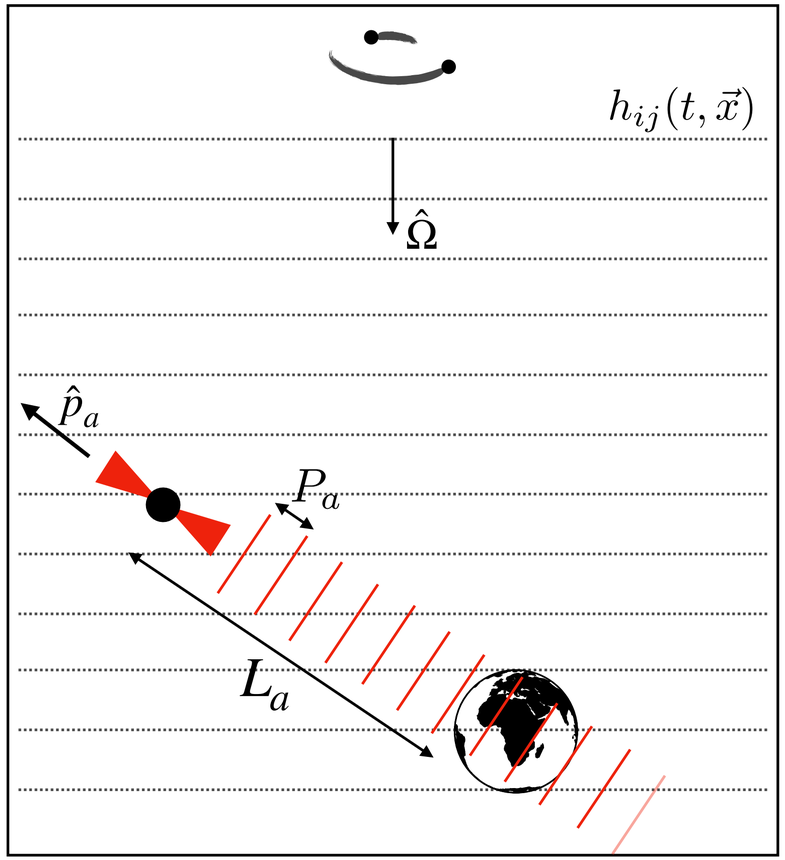


GW SIGNALS



GW SIGNALS

$$\frac{\delta P_a(t)}{P_a} = \frac{\hat{p}_a^i \hat{p}_a^j}{2(1+\hat{\Omega}\cdot\hat{p}_a)}\left[h_{ij}(t,\vec{0}) - h_{ij}(t-L_a, L_a\hat{p}_a)\right]$$



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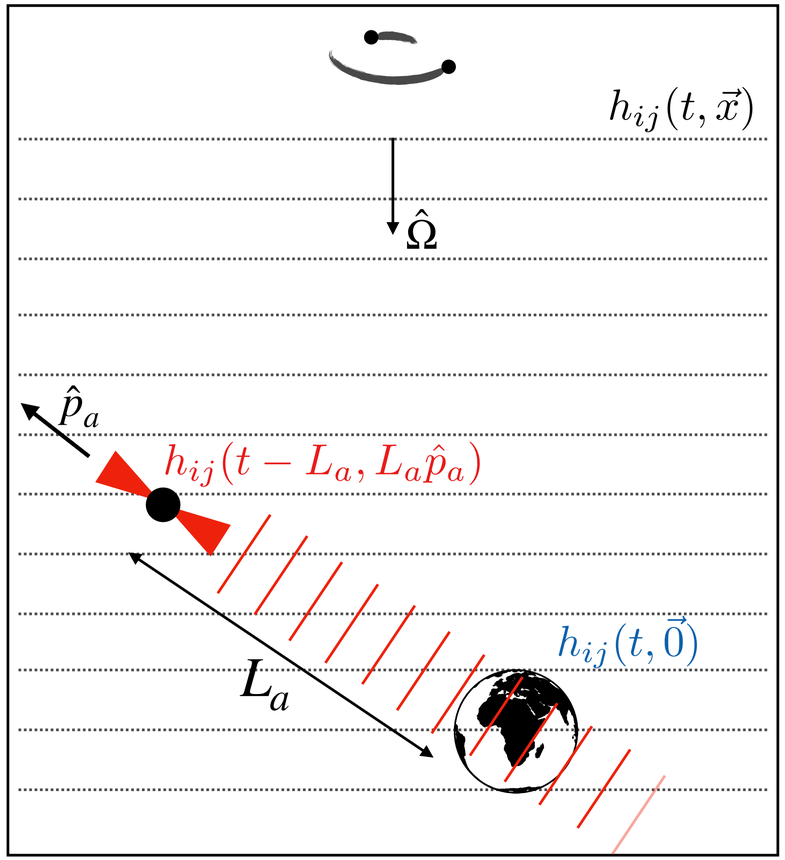
Earth term

pulsar term



GW SIGNALS

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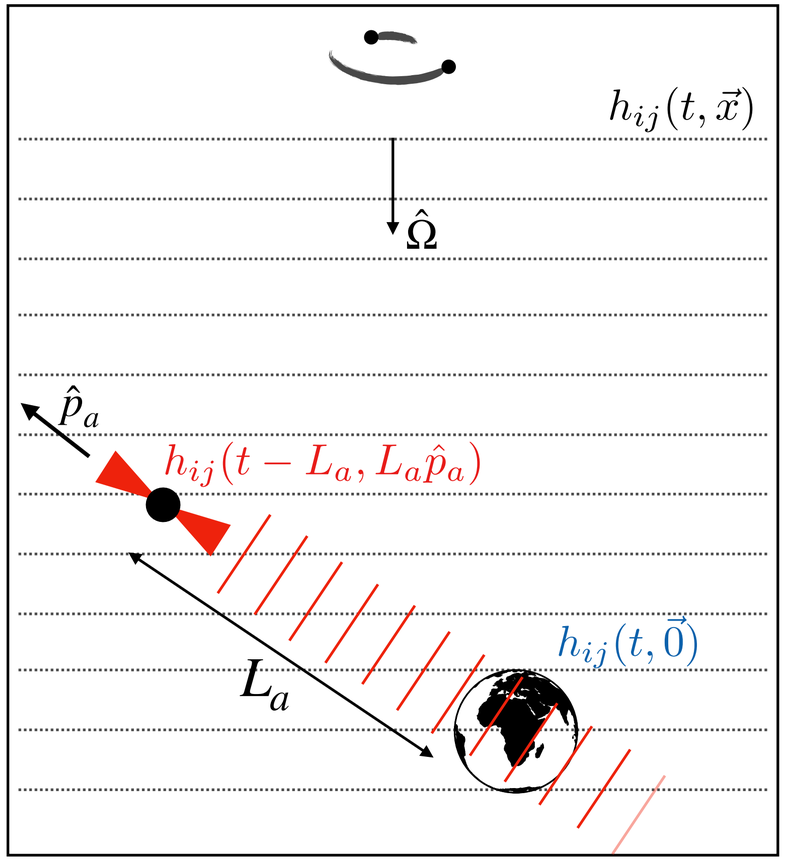
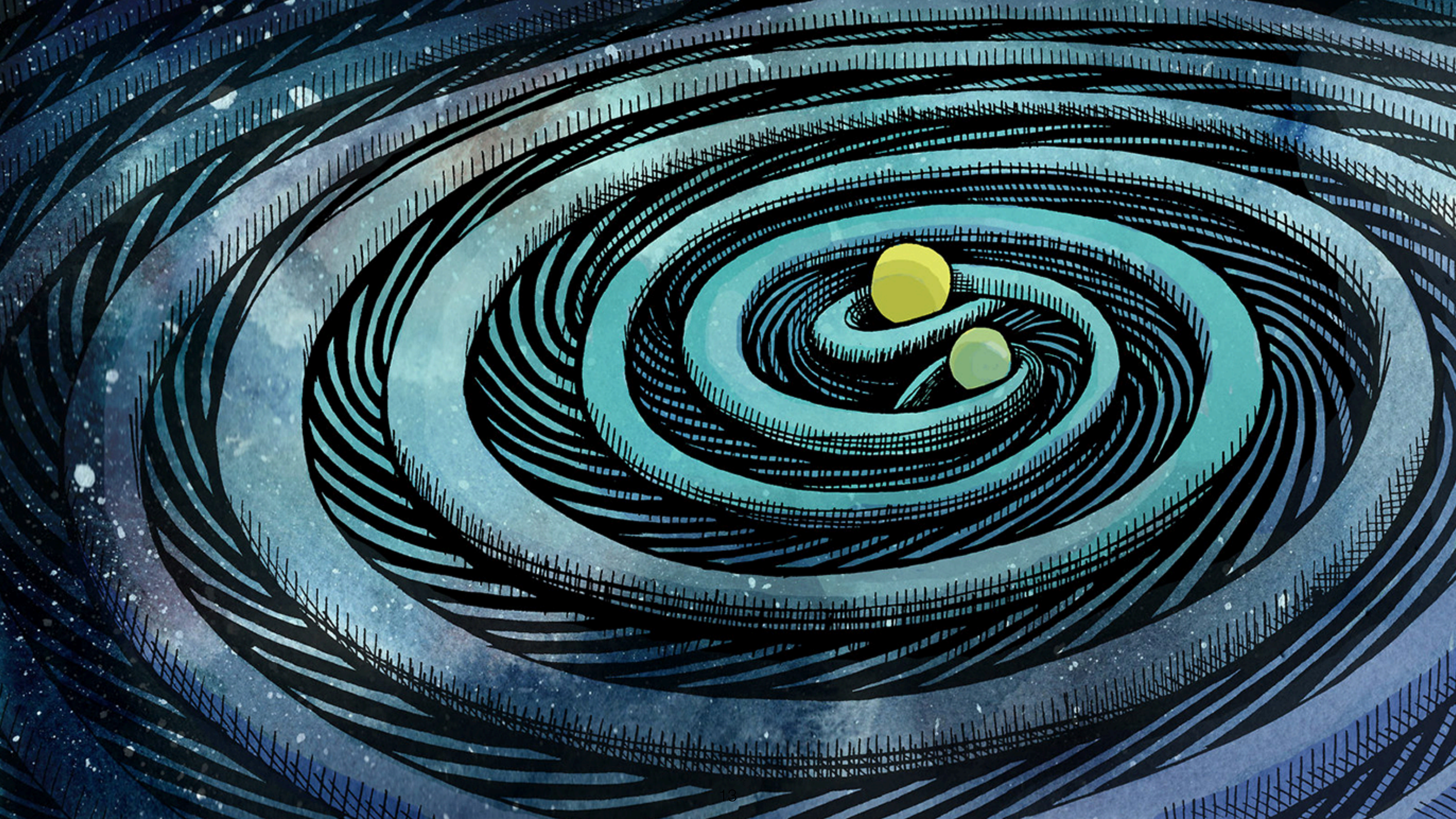
Earth term

pulsar term

geometric response





CONTINUOUS WAVE

$$h_{ij}(t, \vec{x}) \sim h_0 \sin\left[\omega\left(t - \hat{\Omega}\cdot\vec{x}\right)\right] e_{ij}(\hat{\Omega})$$

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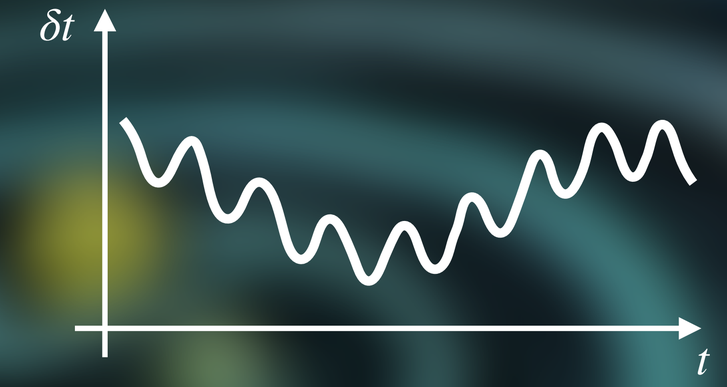

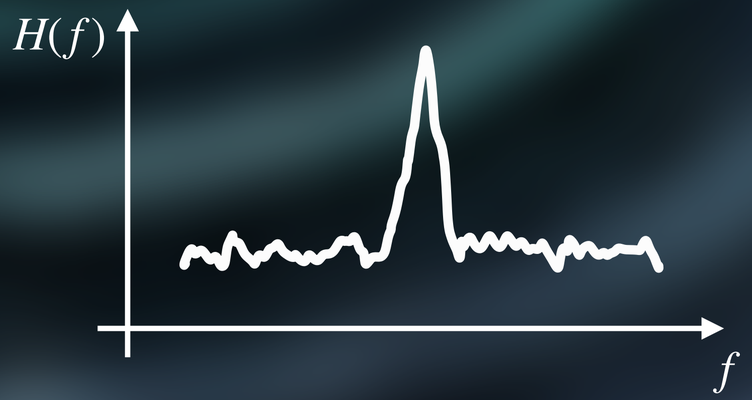

GW BACKGROUND

$$h_{ij}(t,\vec{x}) = \sum_A \int df \int d\hat{\Omega}\; \tilde{h}_A(f,\hat{\Omega})\, e^A_{ij}(\hat{\Omega})\, e^{-2\pi i f(t-\hat{\Omega}\cdot\vec{x})}$$

GW BACKGROUND

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polarization tensors

"Fourier" components
treated as random variables

plane waves

GW BACKGROUND

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"Fourier" components treated as random variables

plane waves

$$\langle \tilde{h}_A(f,\hat{\Omega})^* \tilde{h}_A(f',\hat{\Omega}') \rangle \propto \delta(f-f')H(f)$$

GW BACKGROUND

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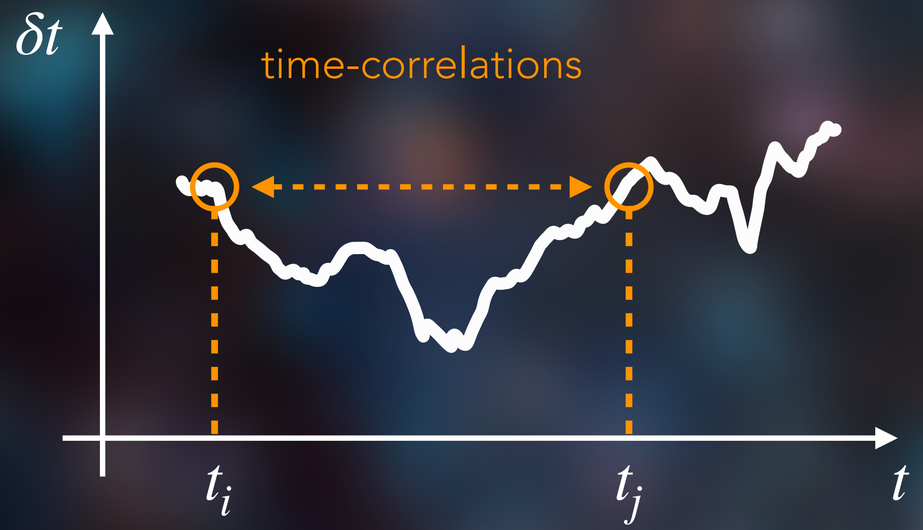

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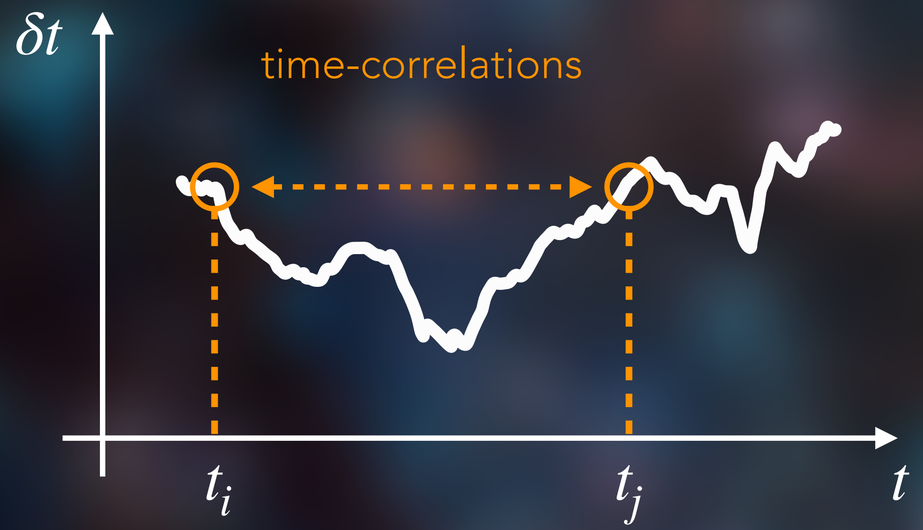

$$\langle \delta t(t_i)\delta t(t_j)\rangle$$

GW BACKGROUND

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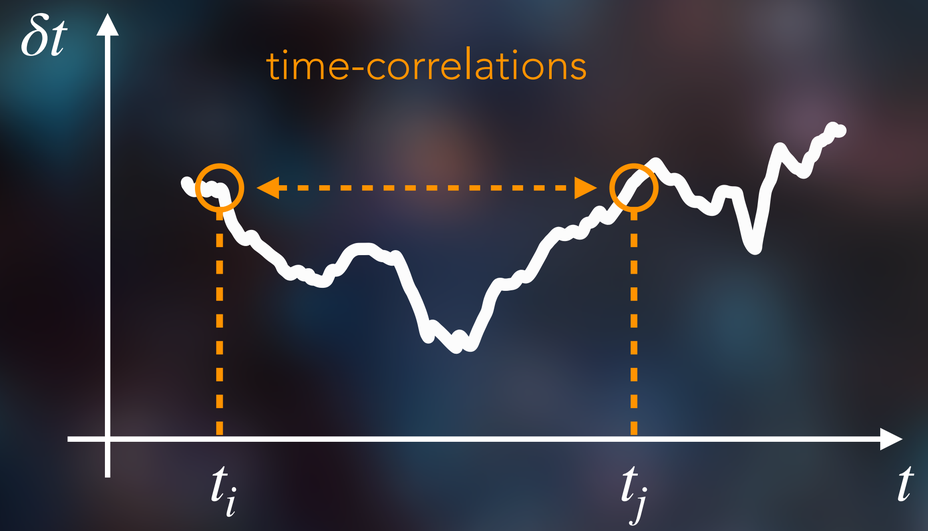


GWB power spectrum

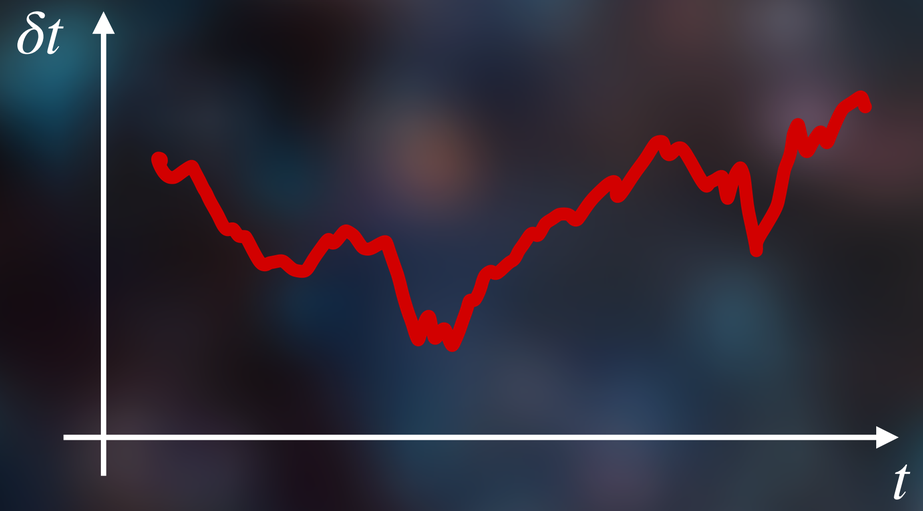
$$\langle \delta t(t_i)\delta t(t_j)\rangle \propto \int df\, H(f)\, e^{2\pi i f(t_i-t_j)}$$

$$\langle \tilde{h}_A(f,\hat{\Omega})^* \tilde{h}_A(f',\hat{\Omega}')\rangle \propto \delta(f-f')H(f)$$

time-correlations of the signal are controlled by the GWB power spectrum

GW BACKGROUND

$$h_{ij}(t,\vec{x}) = \sum_A \int df \int d\hat{\Omega}\; \tilde{h}_A(f,\hat{\Omega})\, e^A_{ij}(\hat{\Omega})\, e^{-2\pi i f(t-\hat{\Omega}\cdot\vec{x})}$$



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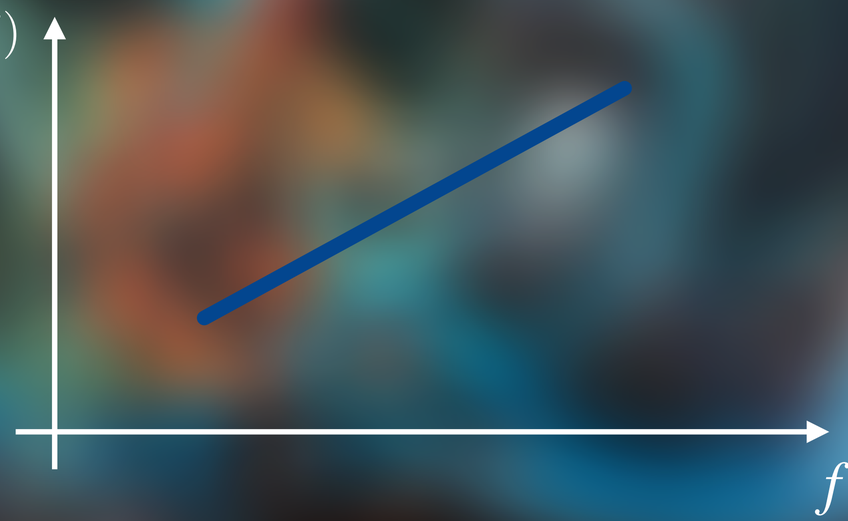

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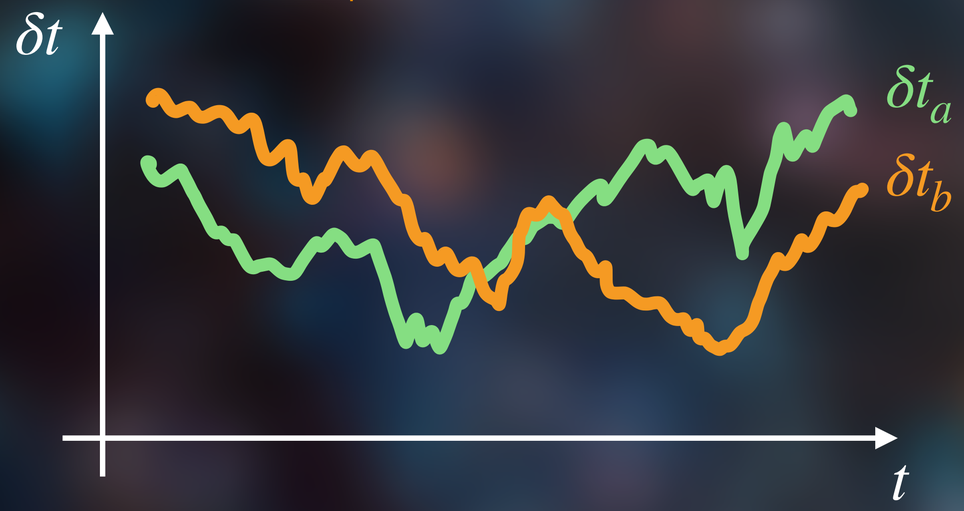
spatial correlations



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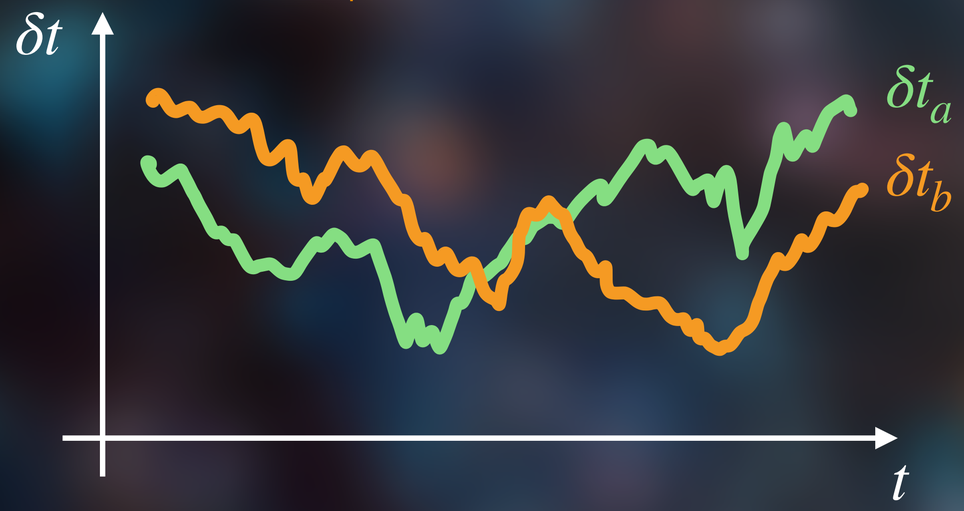
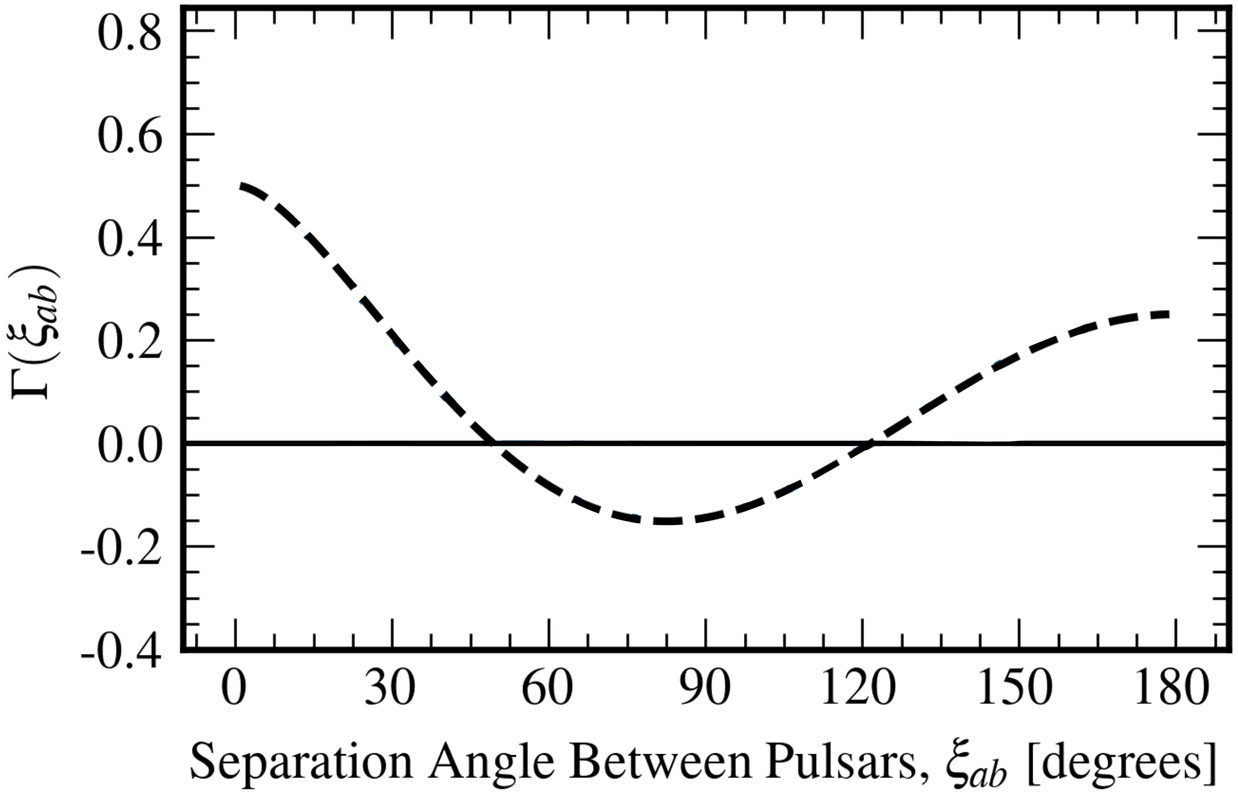


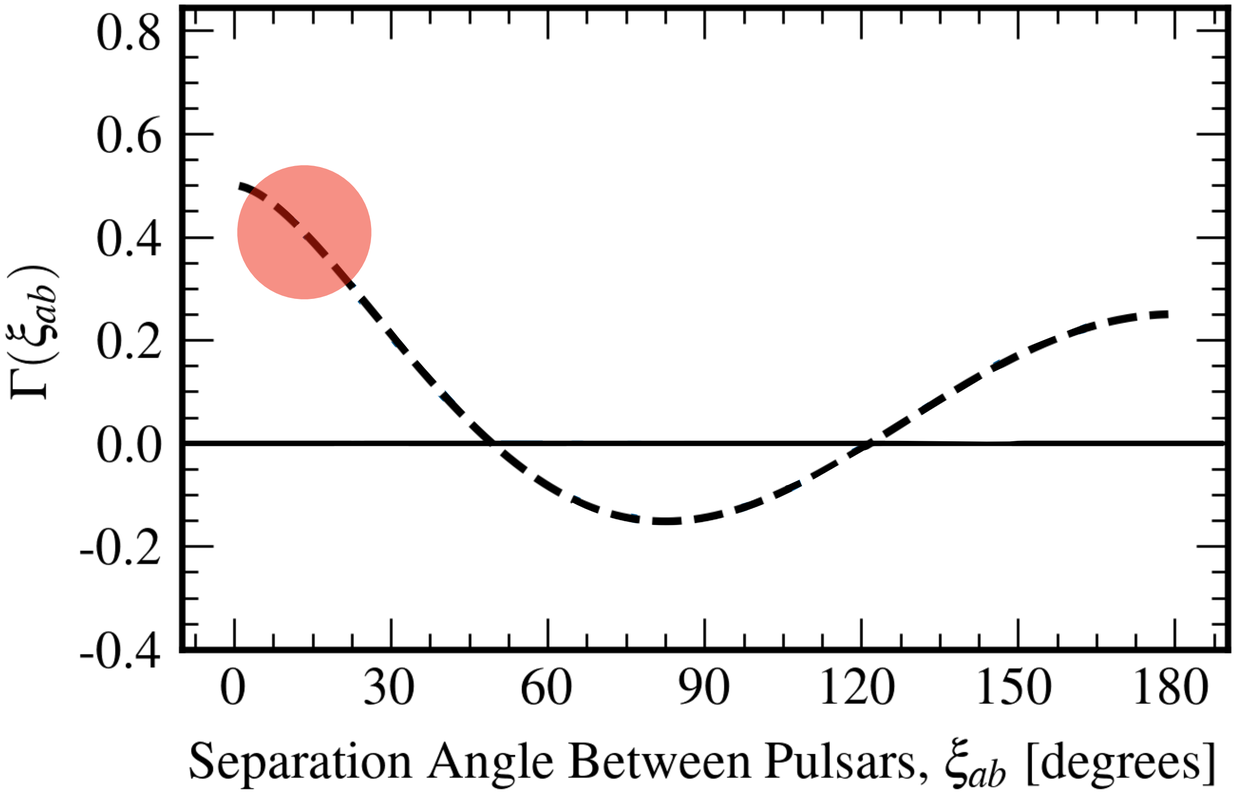
$$\langle \delta t_a \delta t_b \rangle \propto \Gamma_{ab}$$

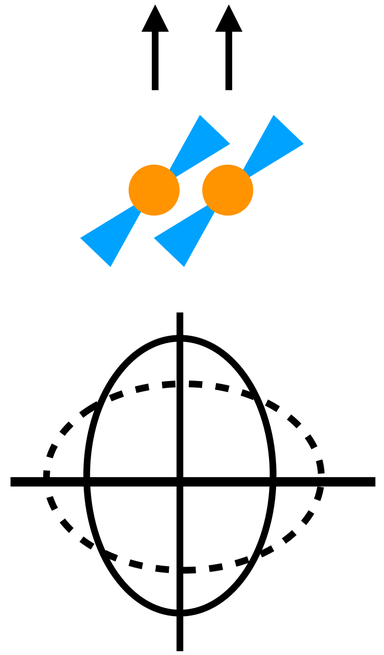
$$\Gamma_{ab} = \int d\hat{\Omega} \sum_A F^A_a(\hat{\Omega}) F^A_b(\hat{\Omega}) [1 + \delta_{ab}]$$

HELLINGS & DOWNS CURVE



HELLINGS & DOWNS CURVE





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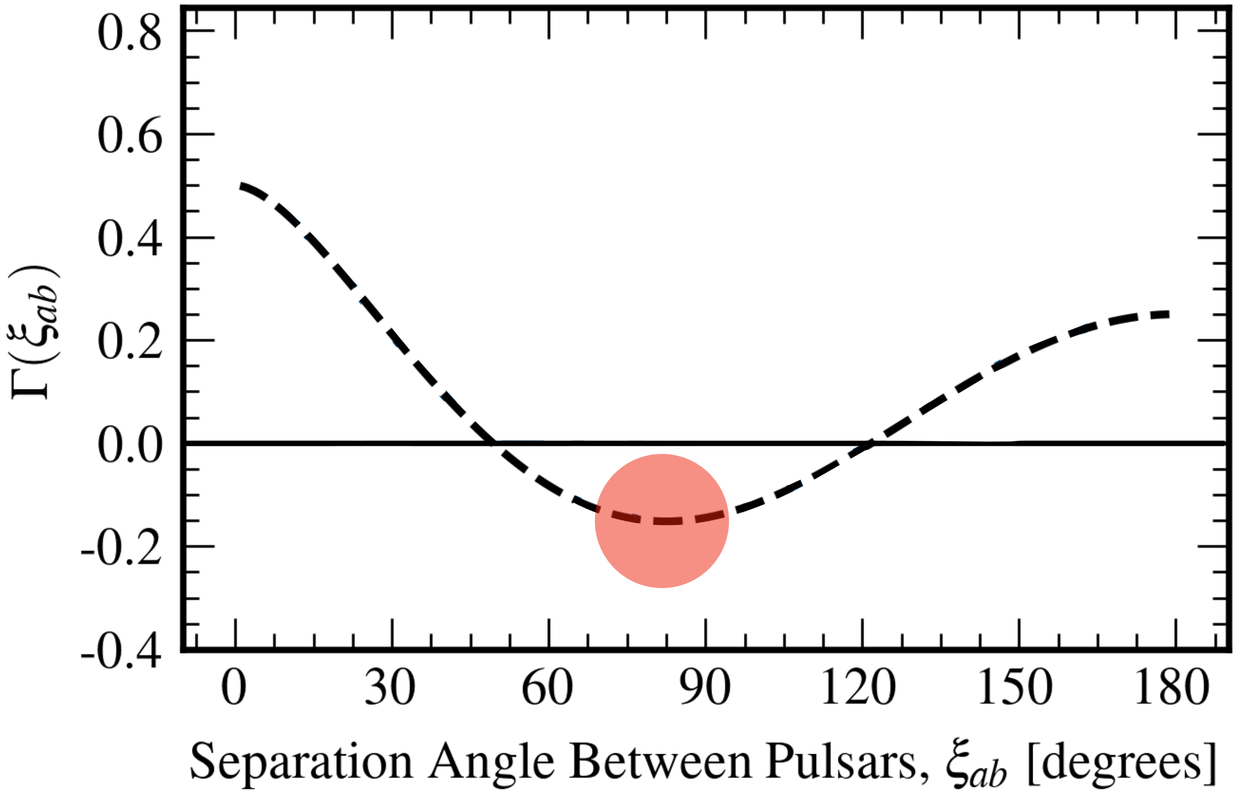

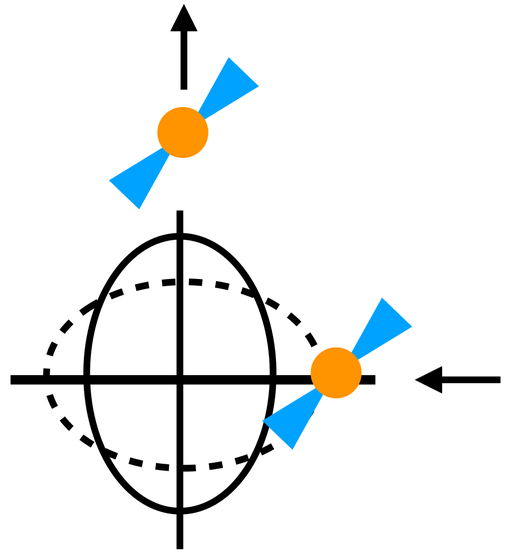

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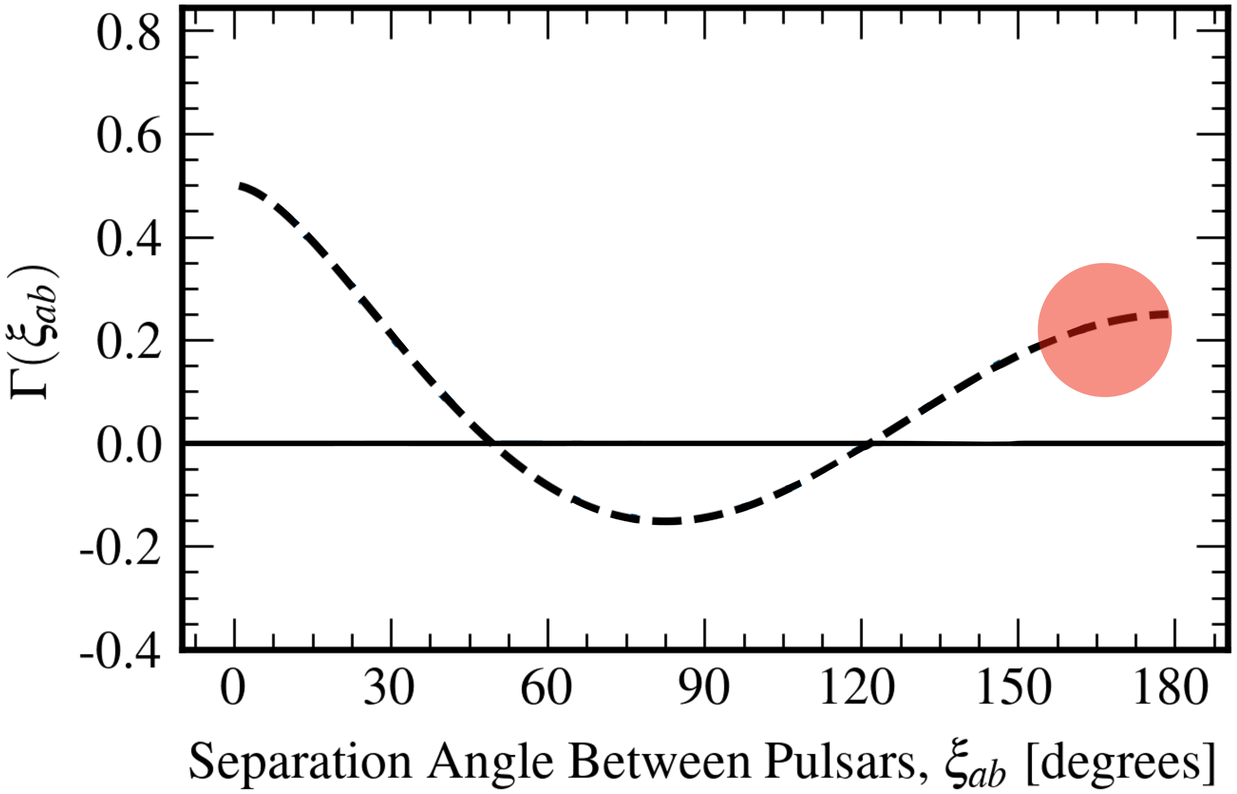
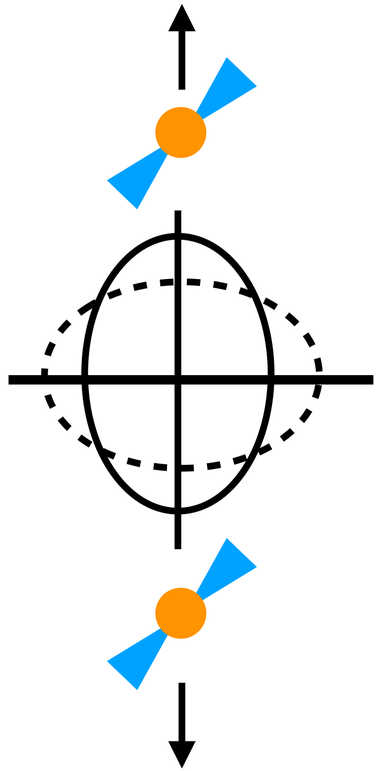




searching for a GWB means searching for **stochastic delays** in the TOAs that are **common across pulsars** and **spatially correlated**

EVIDENCE FOR A GWB

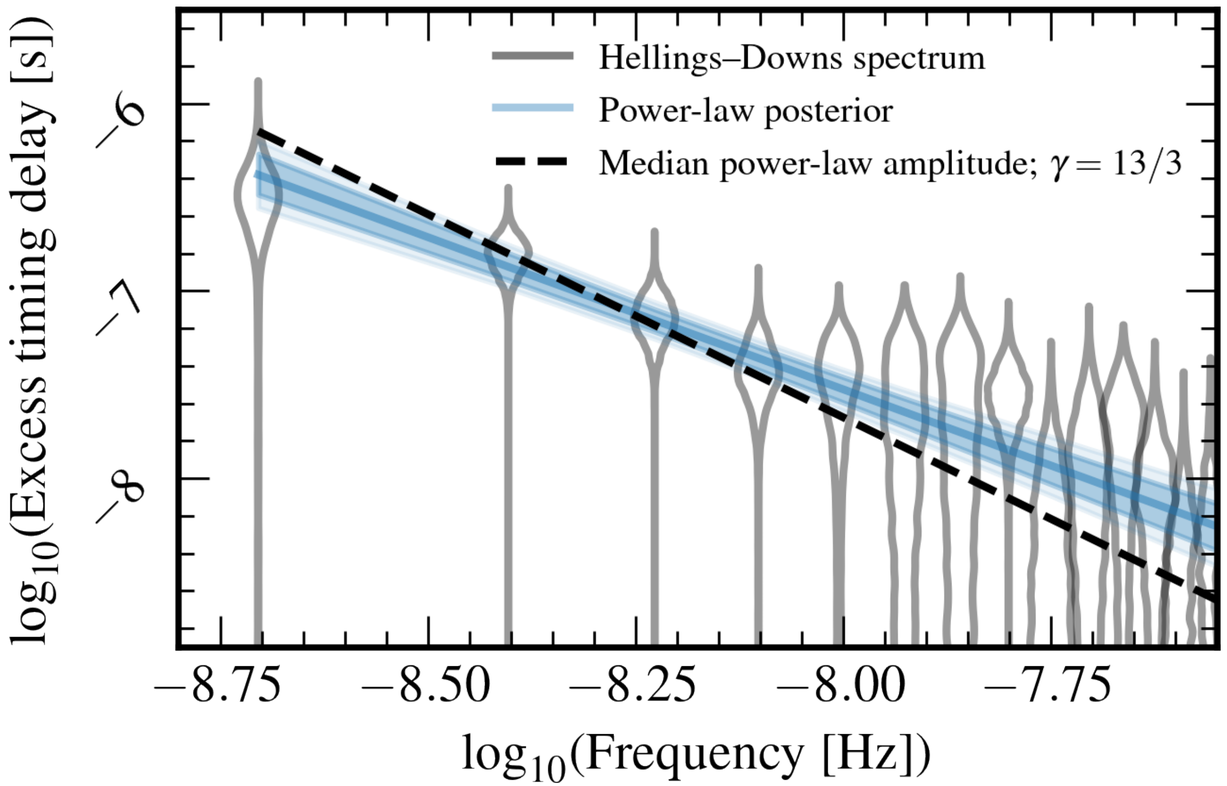
The NANOGrav 15-year Data Set: Evidence for a Gravitational-Wave Background

ABSTRACT

We report multiple lines of evidence for a stochastic signal that is correlated among 67 pulsars from the 15-year pulsar-timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. The correlations follow the Hellings–Downs pattern expected for a stochastic gravitational-wave background. The presence of such a gravitational-wave background with a power-law–spectrum is favored over a model with only independent pulsar noises with a Bayes factor in excess of 10^{14}, and this same model is favored over an uncorrelated common power-law–spectrum model with Bayes factors of 200–1000, depending on spectral modeling choices. We have built a statistical background distribution for these latter Bayes factors using a method that removes inter-pulsar correlations from our data set, finding $p = 10^{-3}$ (approx. 3σ) for the observed Bayes factors in the null no-correlation scenario. A frequentist test statistic built directly as a weighted sum of inter-pulsar correlations yields $p = 5 \times 10^{-5}$–1.9×10^{-4} (approx. 3.5–4σ). Assuming a fiducial $f^{-2/3}$ characteristic-strain spectrum, as appropriate for an ensemble of binary supermassive black-hole inspirals, the strain amplitude is $2.4^{+0.7}_{-0.6} \times 10^{-15}$ (median + 90% credible interval) at a reference frequency of 1 yr^{-1}. The inferred gravitational-wave background amplitude and spectrum are consistent with astrophysical expectations for a signal from a population of supermassive black-hole binaries, although more exotic cosmological and astrophysical sources cannot be excluded. The observation of Hellings–Downs correlations points to the gravitational-wave origin of this signal.

EVIDENCE FOR GWB

$$\langle \delta t_a(t_i) \delta t_b(t_j) \rangle \propto \Gamma_{ab} \int df \; H(f) \; e^{2\pi i f (t_i - t_j)}$$



we find evidence for Hellings & Downs correlation with a p-value of $5 \times 10^{-5} - 1.9 \times 10^{-4}$ (approx. $3.5 - 4\sigma$)

NANOGrav [including **AM**], *"The NANOGrav 15yr Data Set: Evidence for a for a Gravitational-Wave Background"*, ApJL 951, L8(2023).

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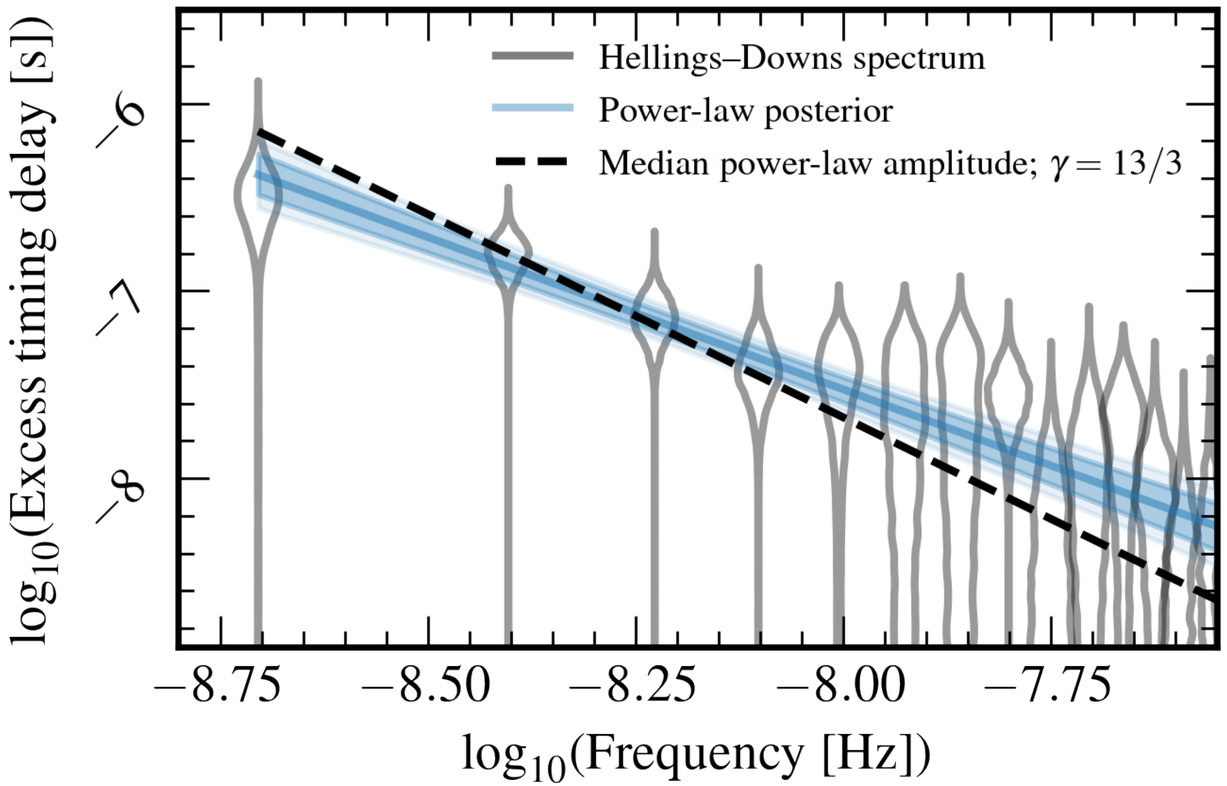

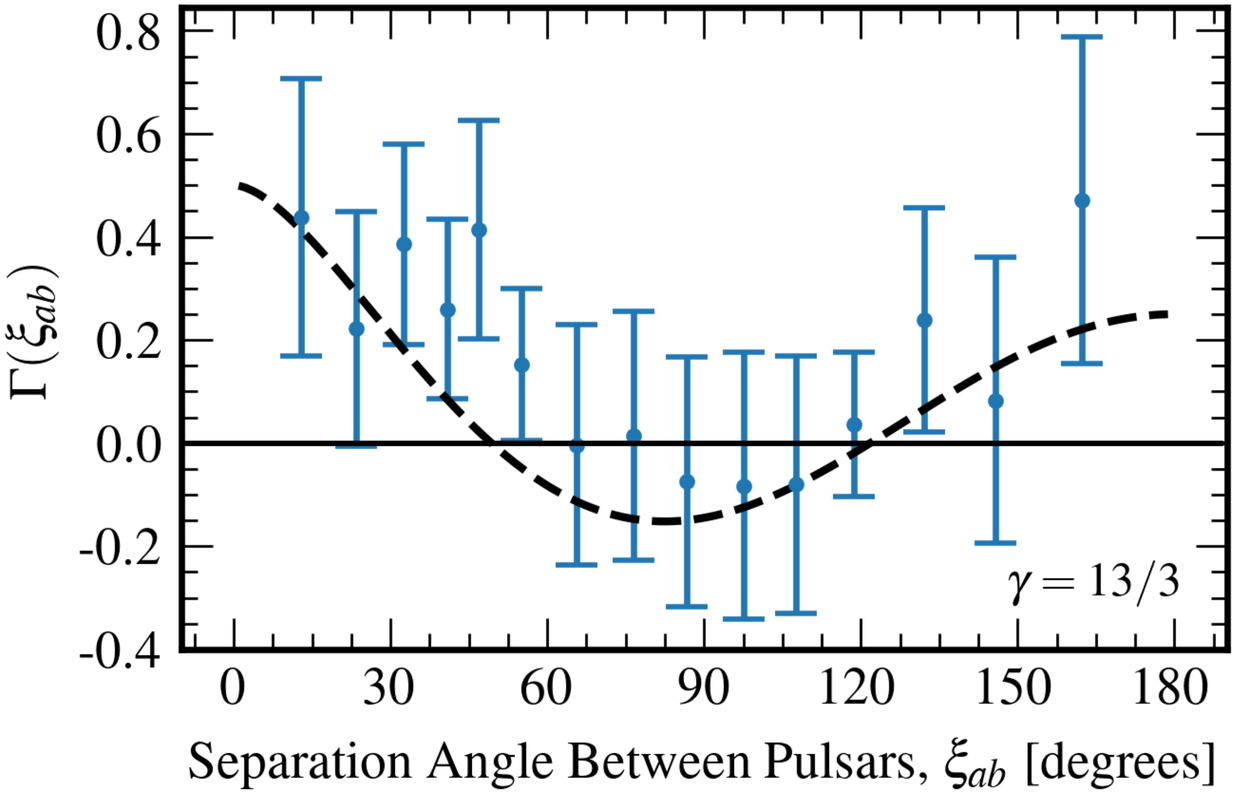

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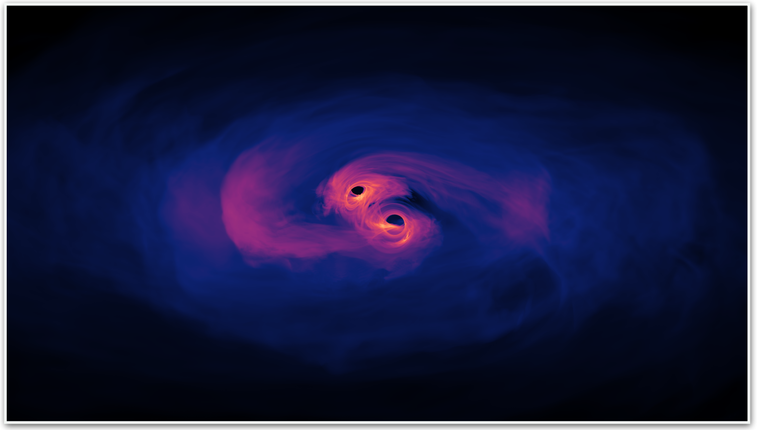
NANOGrav [including **AM**], *"The NANOGrav 15yr Data Set: Evidence for a for a Gravitational-Wave Background"*, ApJL 951, L8(2023).

what is the source?

ASTRO OR COSMO?



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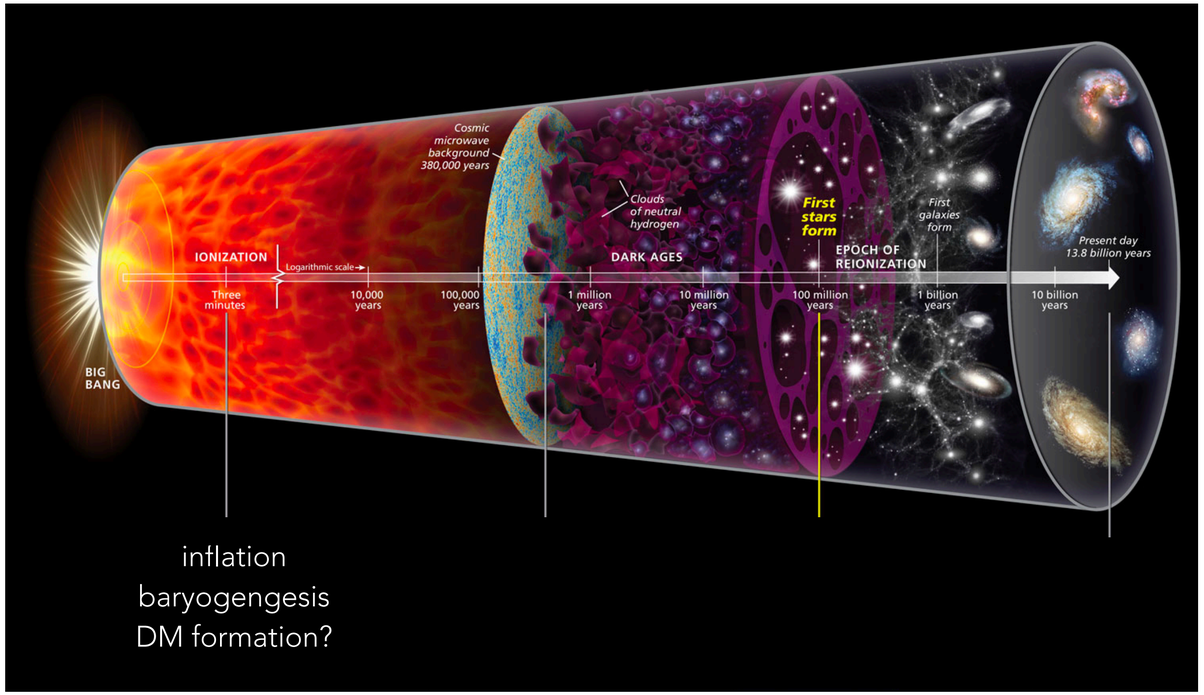
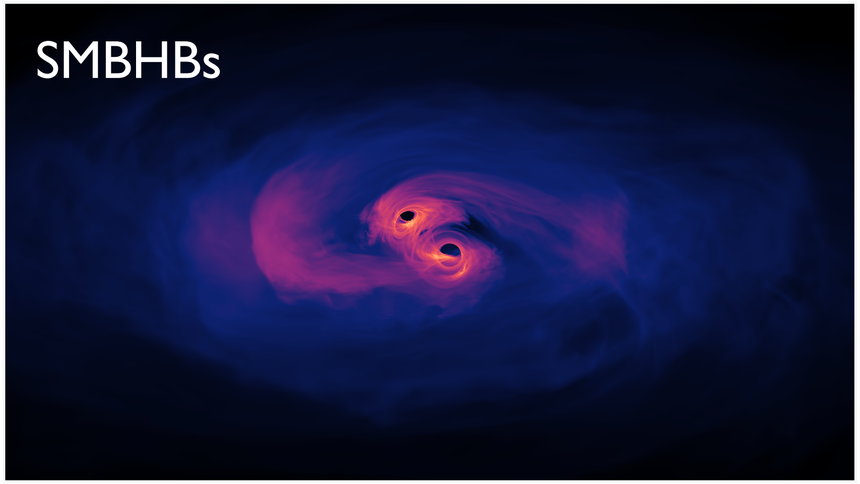


inflation
baryogengesis
DM formation?

VS



ASTRO OR COSMO?

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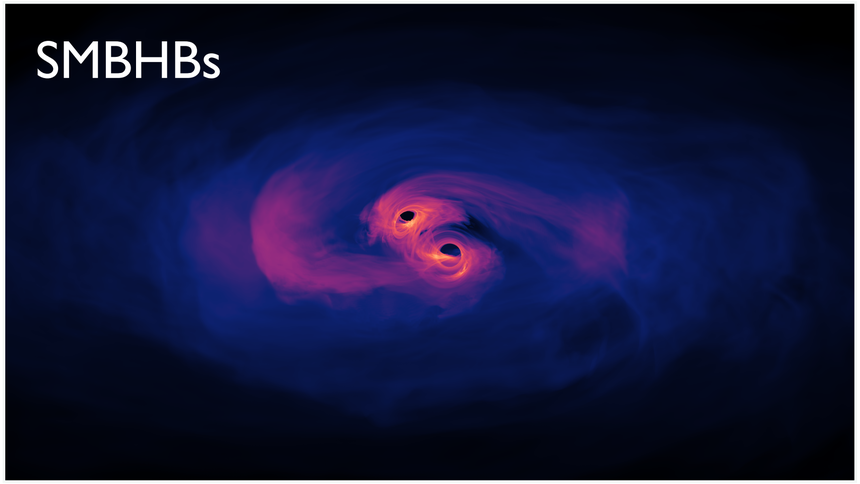

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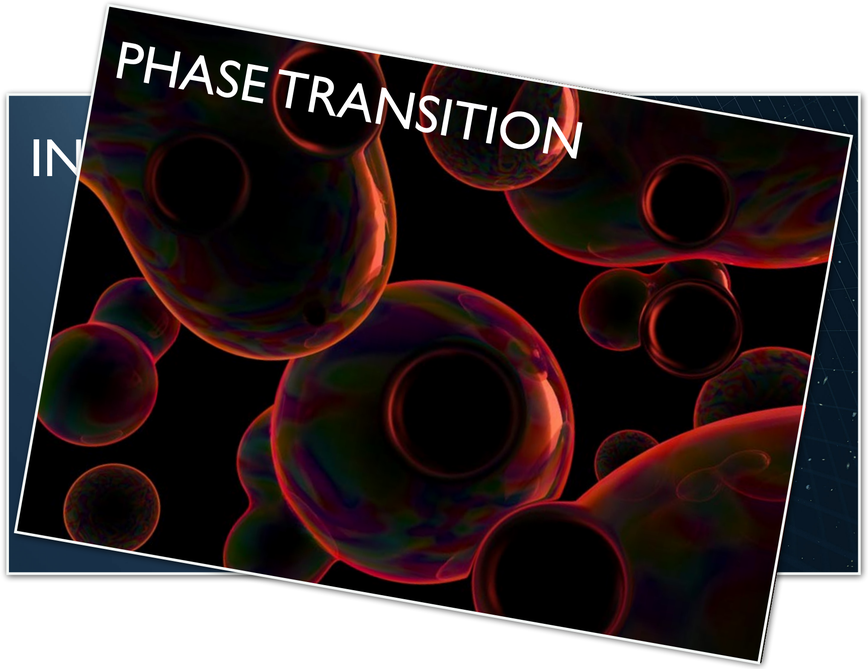

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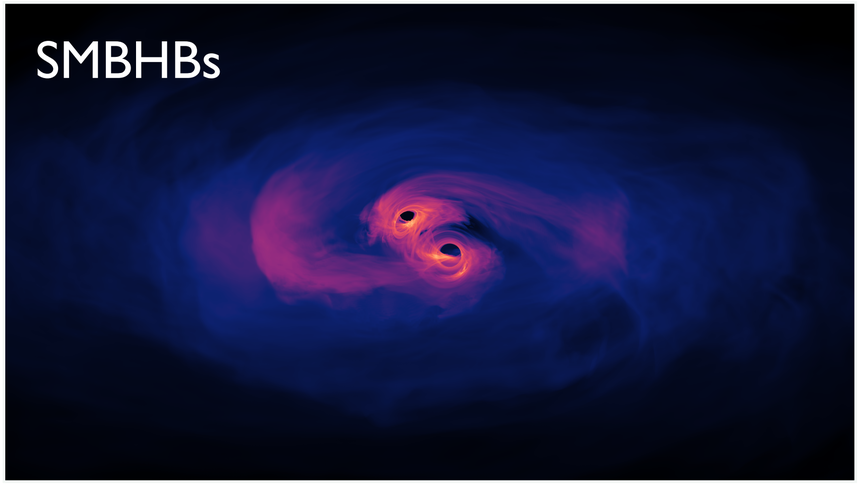

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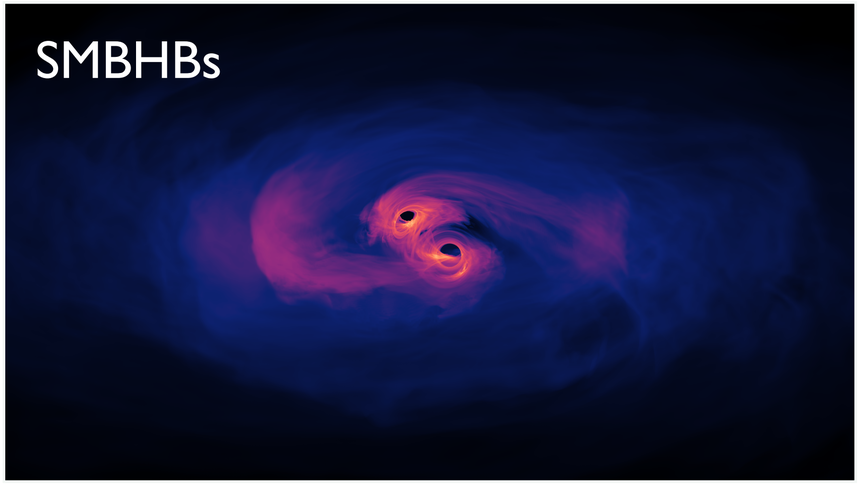

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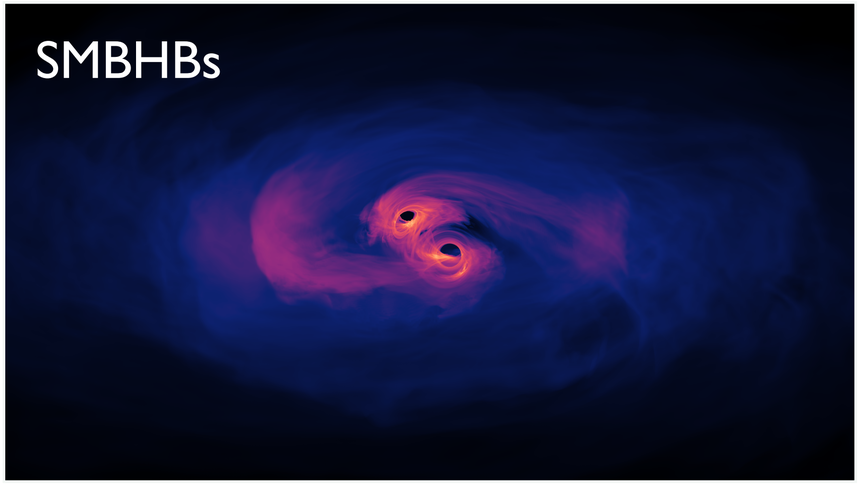
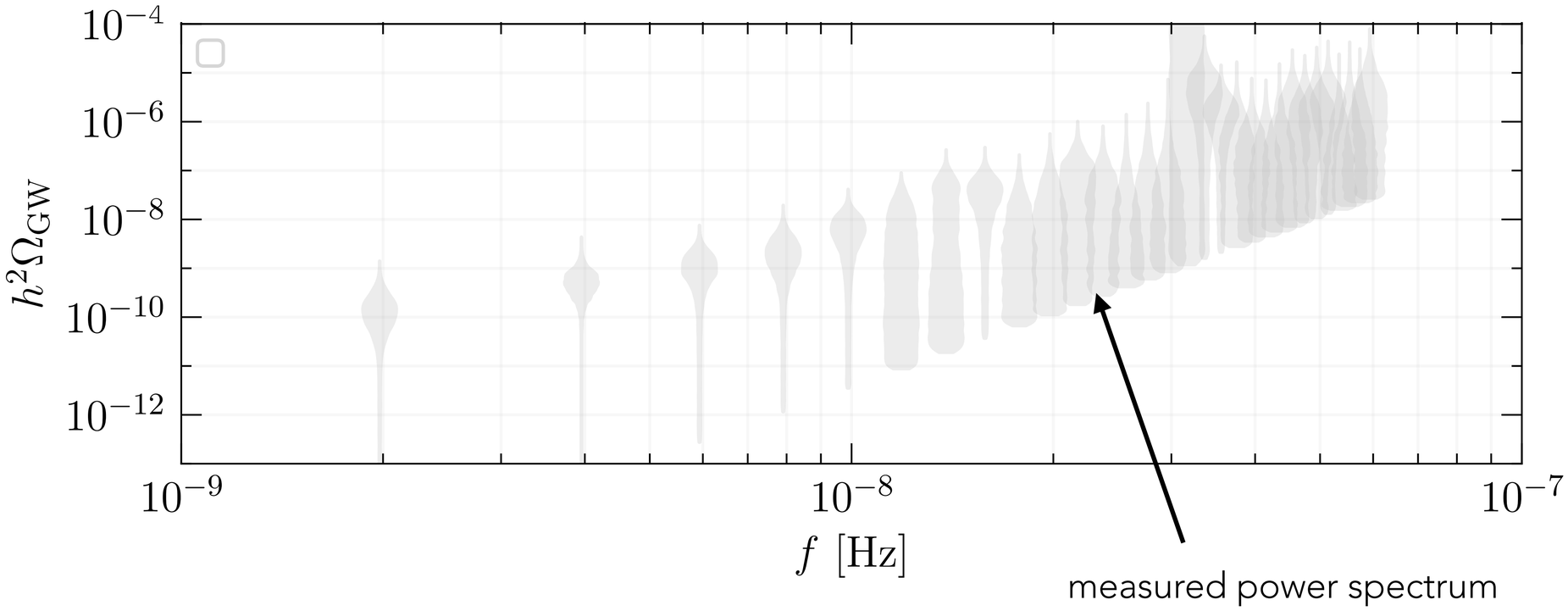


SPECTRAL DISCRIMINATION



NANOGrav [inc. **AM** as corresponding author], *"The NANOGrav 15yr Data Set: Search for Signals from New Physics"*, ApJL 951, L11(2023).

SPECTRAL DISCRIMINATION

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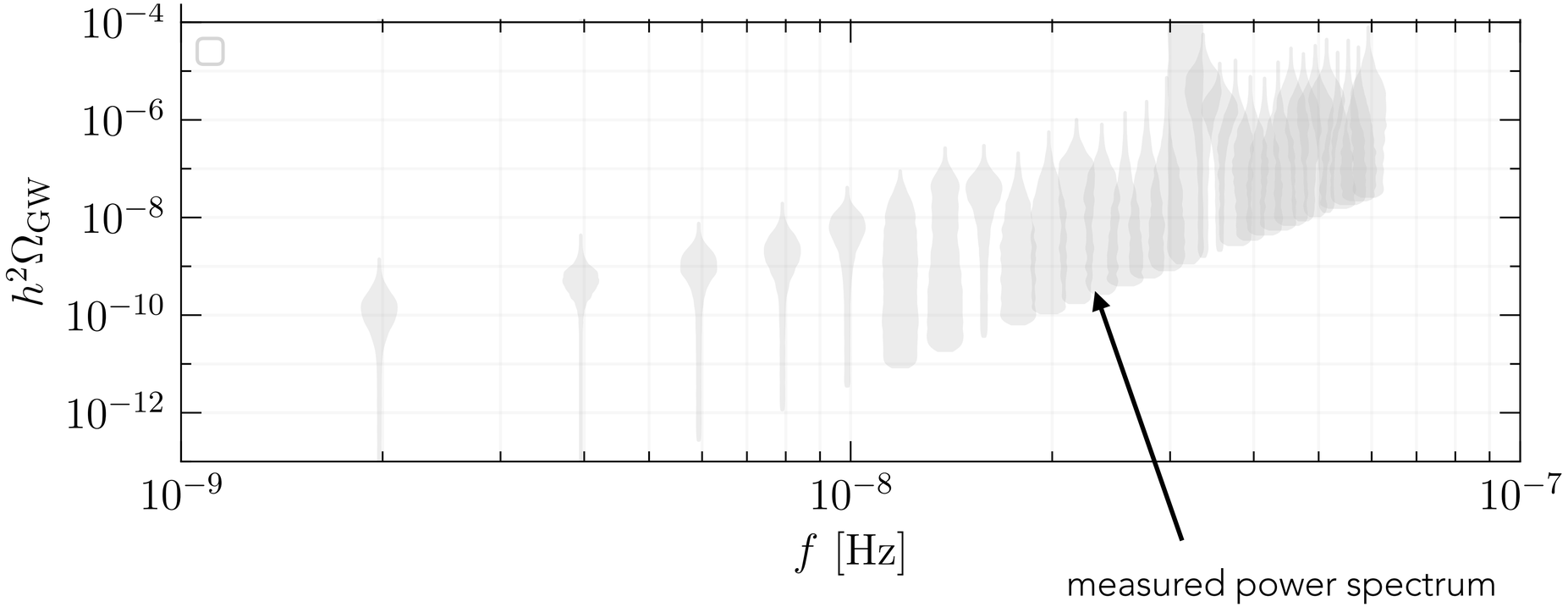

NANOGrav [inc. **AM** as corresponding author], *"The NANOGrav 15yr Data Set: Search for Signals from New Physics"*, ApJL 951, L11(2023).

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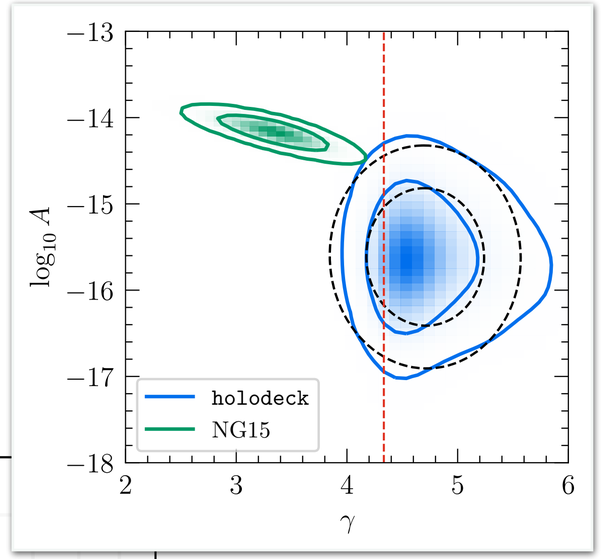

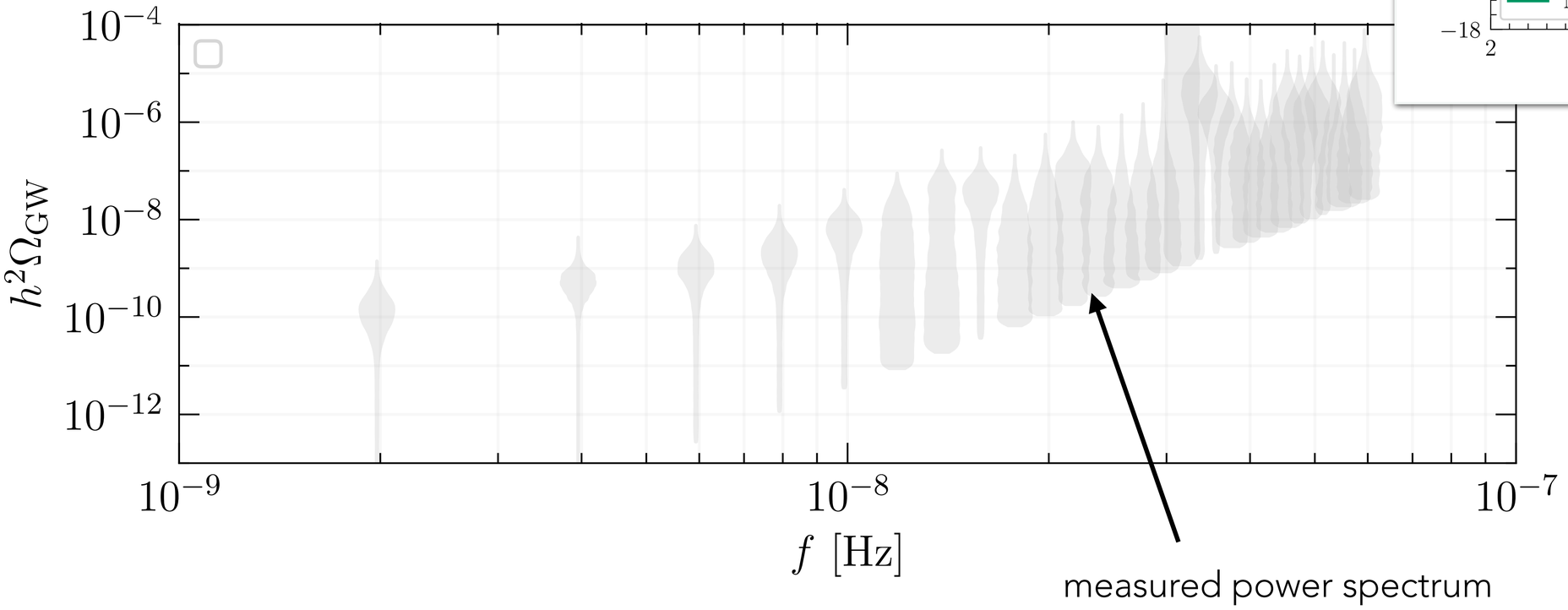

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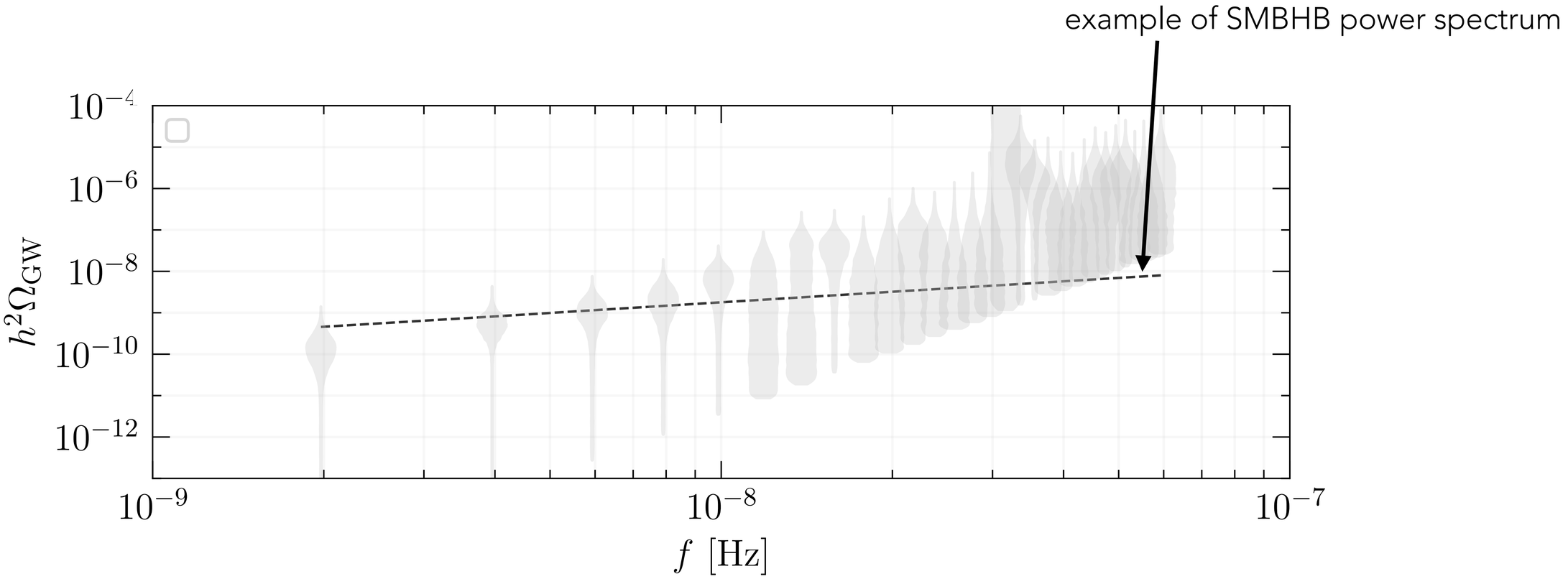

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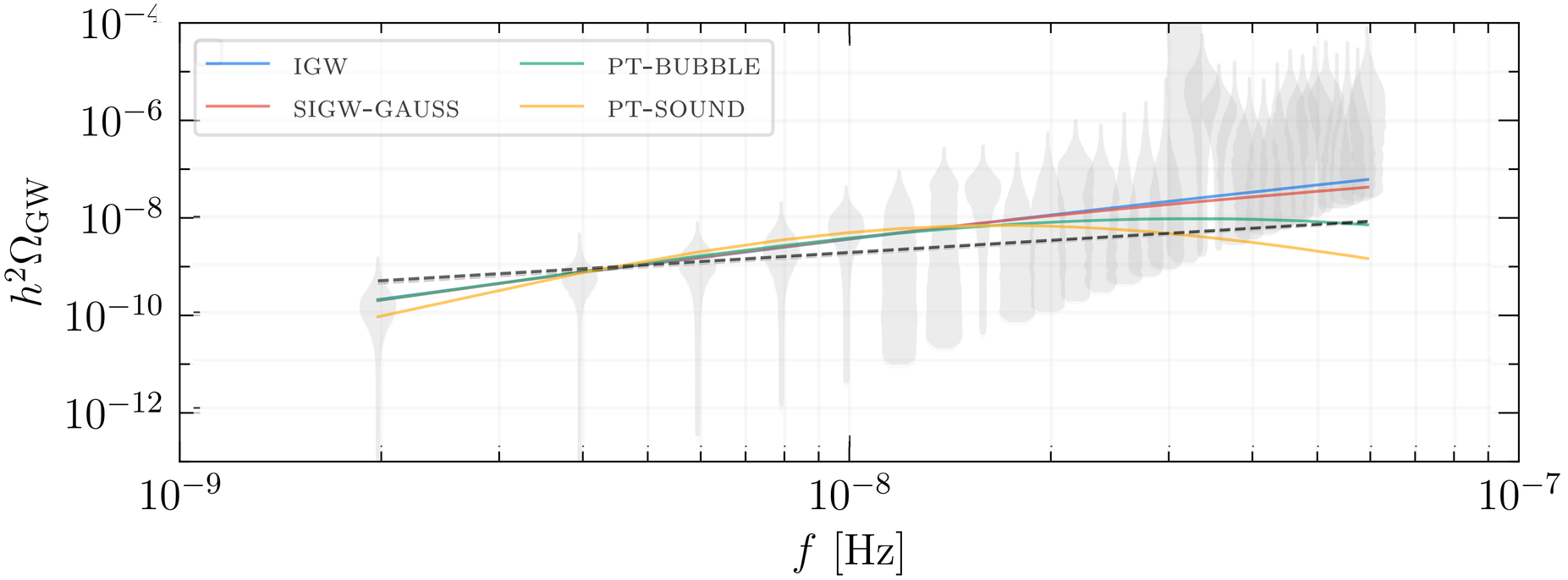

NANOGrav [inc. **AM** as corresponding author], *"The NANOGrav 15yr Data Set: Search for Signals from New Physics"*, ApJL 951, L11(2023).

SPECTRAL DISCRIMINATION

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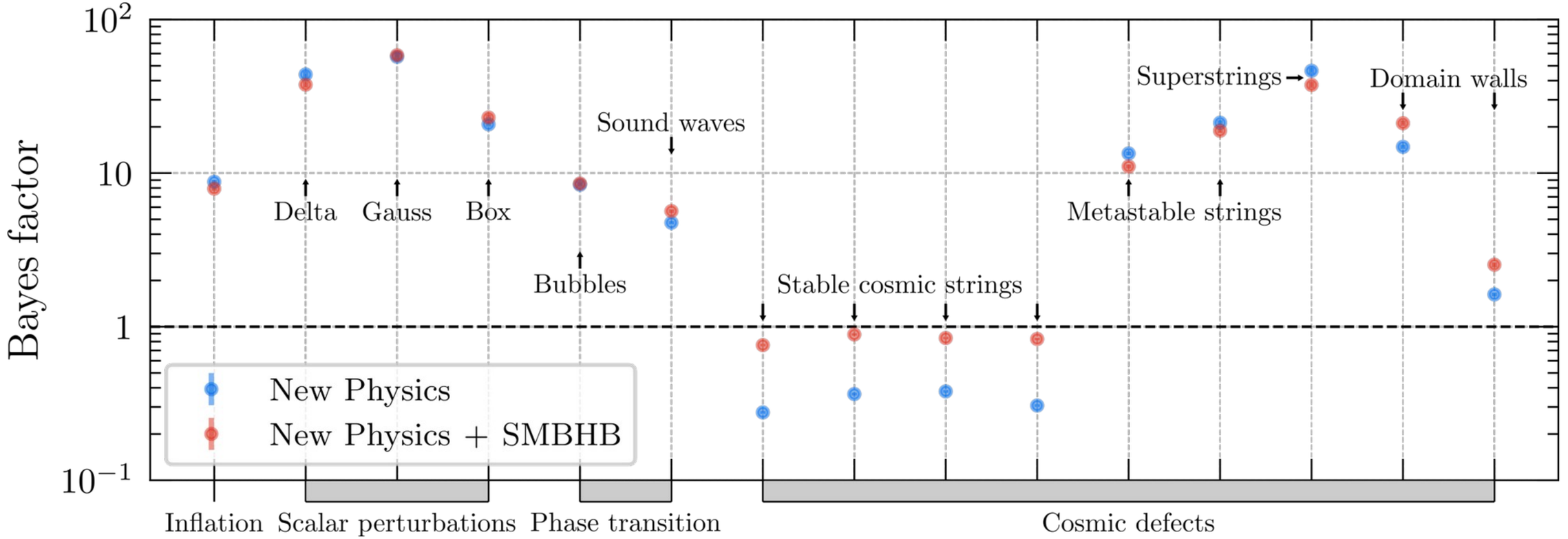
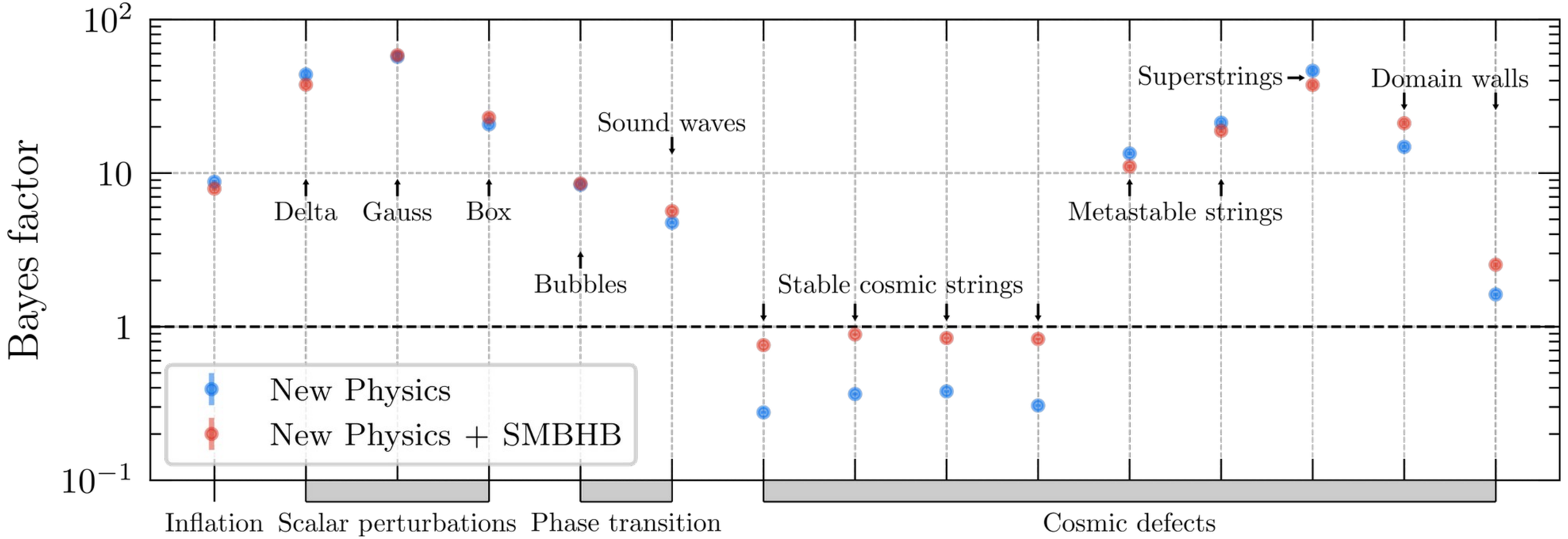


NANOGrav [inc. **AM** as corresponding author], *"The NANOGrav 15yr Data Set: Search for Signals from New Physics"*, ApJL 951, L11(2023).

SPECTRAL DISCRIMINATION

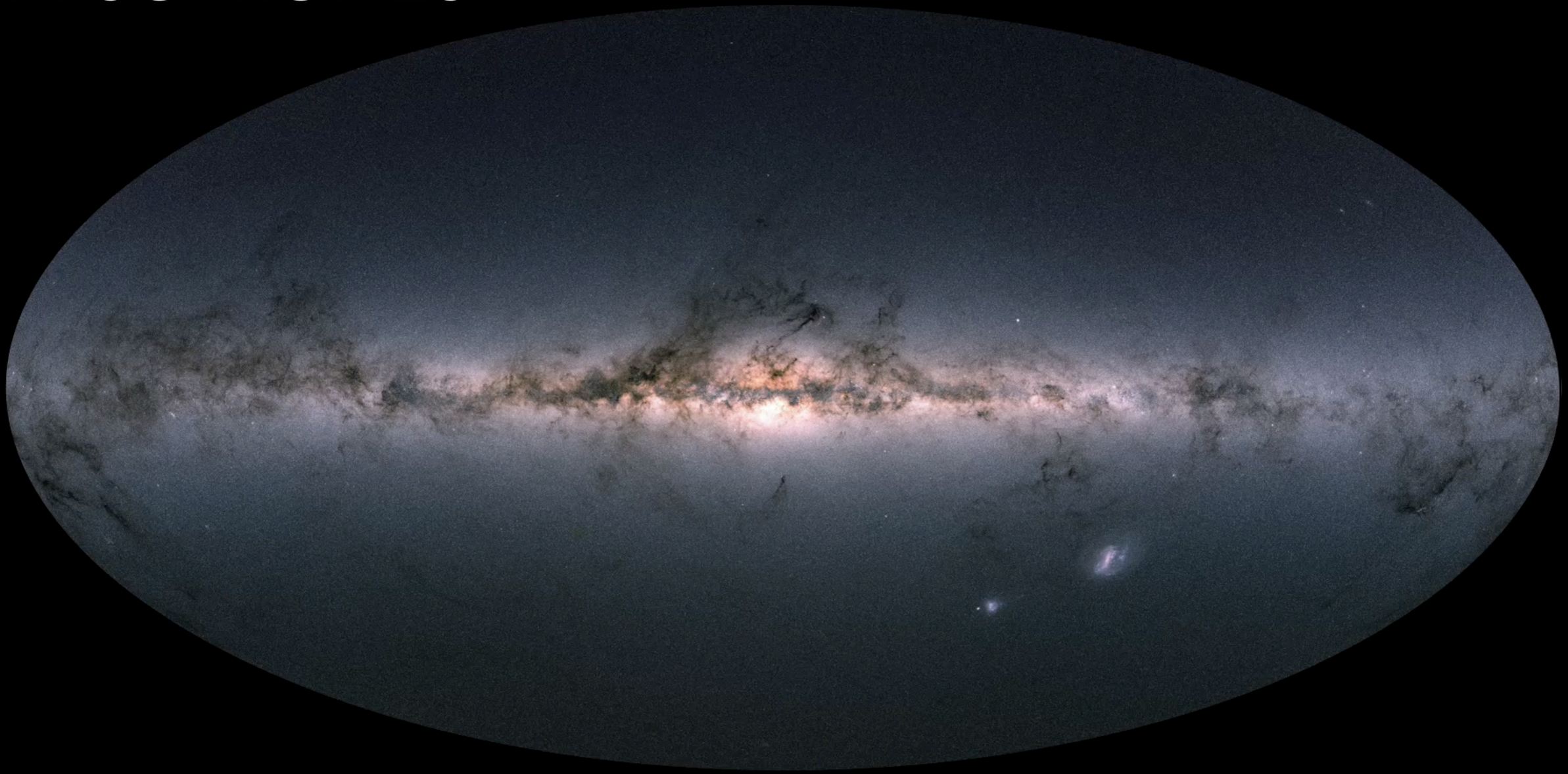
many cosmological models seem to be preferred over SMBHB…
…however, systematic uncertainties are still to large to make a definitive claim



NANOGrav [inc. **AM** as corresponding author], *"The NANOGrav 15yr Data Set: Search for Signals from New Physics"*, ApJL 951, L11(2023).

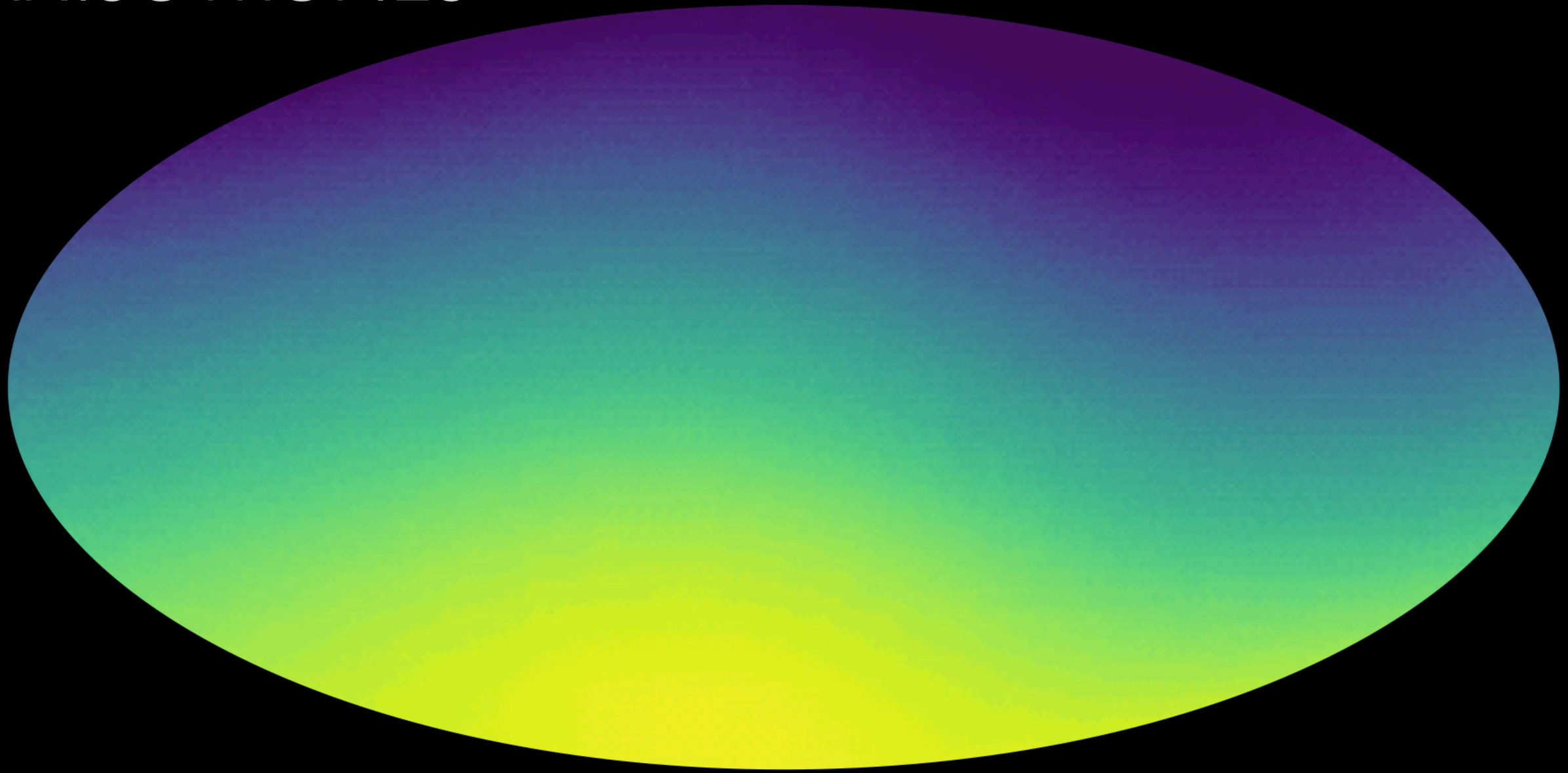
what now?

ANISOTROPIES



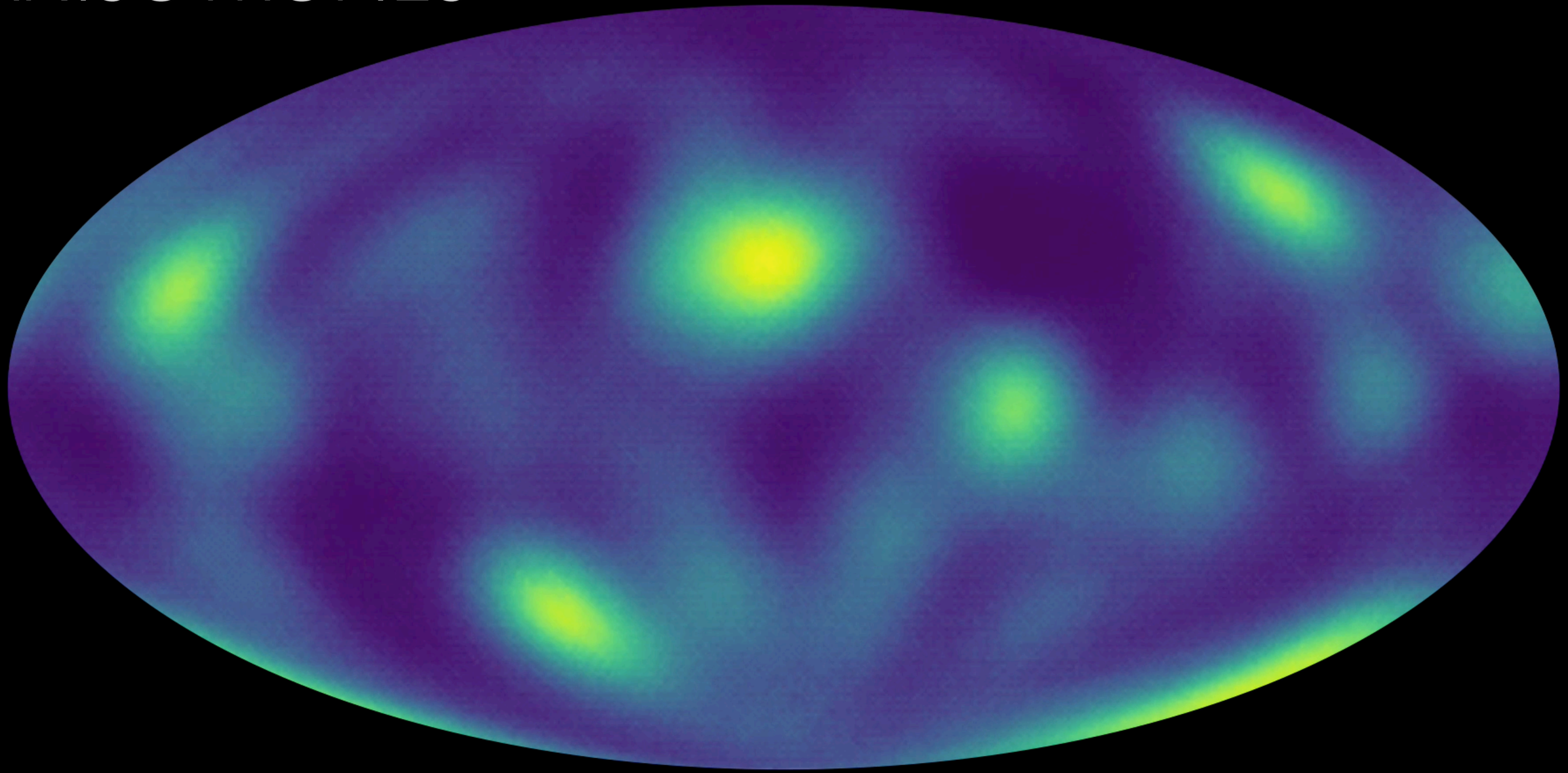
Credit: ESA/Gaia/DPAC

ANISOTROPIES



Simulated Data

ANISOTROPIES



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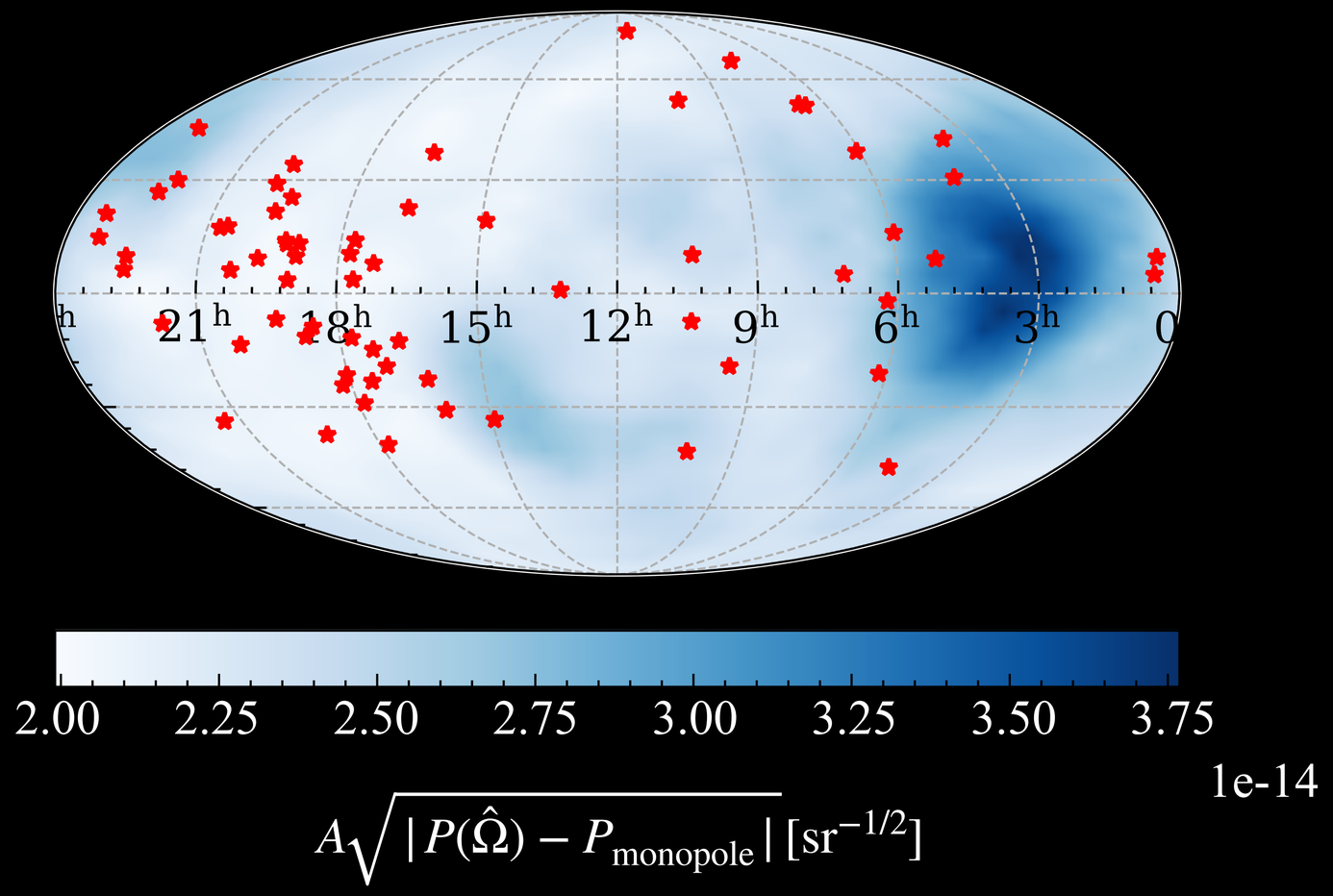

no statistically significant deviation from isotropy

NANOGrav [including **AM**], *"The NANOGrav 15-year Data Set: Search for Anisotropy in the Gravitational-Wave Background"*, ApJL. 956 (2023) 1, L3

THE PATH FORWARD

what does these null detections teach us?

→ is there a tension between these null detections and the SMBHB intepretation of the GWB?

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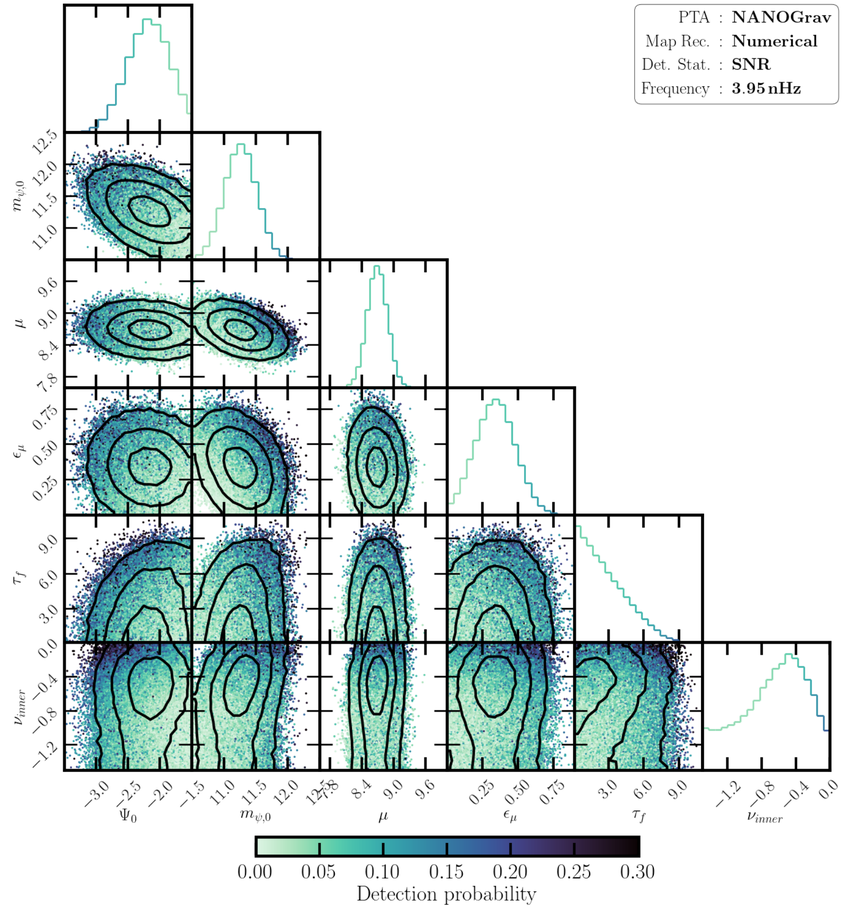
Lemke, **AM**, Gersbach, *"Detecting Gravitational Wave Anisotropies from Supermassive Balck Hole Binaries"*, PRD 111, 6 (2025)



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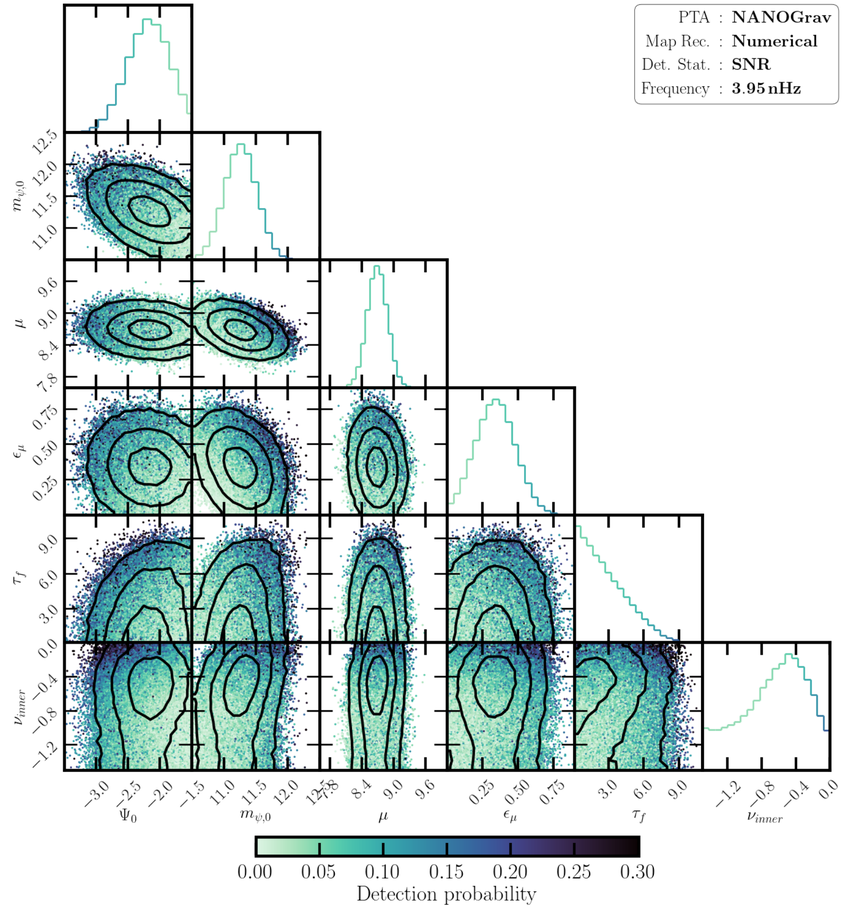
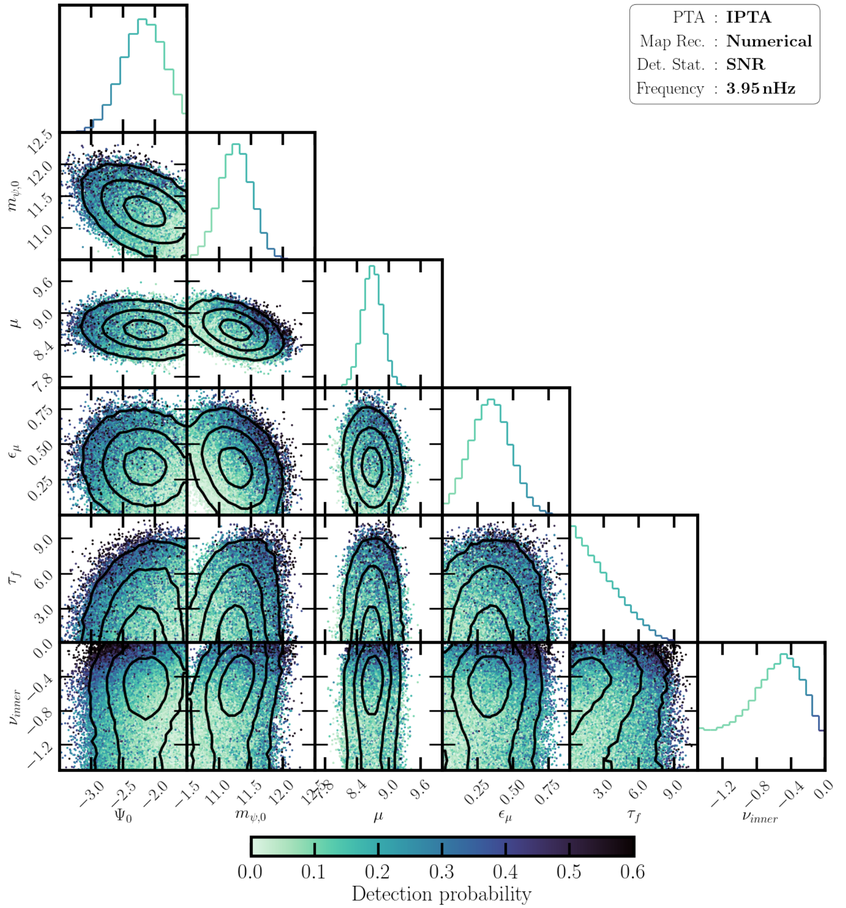
Lemke, **AM**, Gersbach, *"Detecting Gravitational Wave Anisotropies from Supermassive Balck Hole Binaries"*, PRD 111, 6 (2025)





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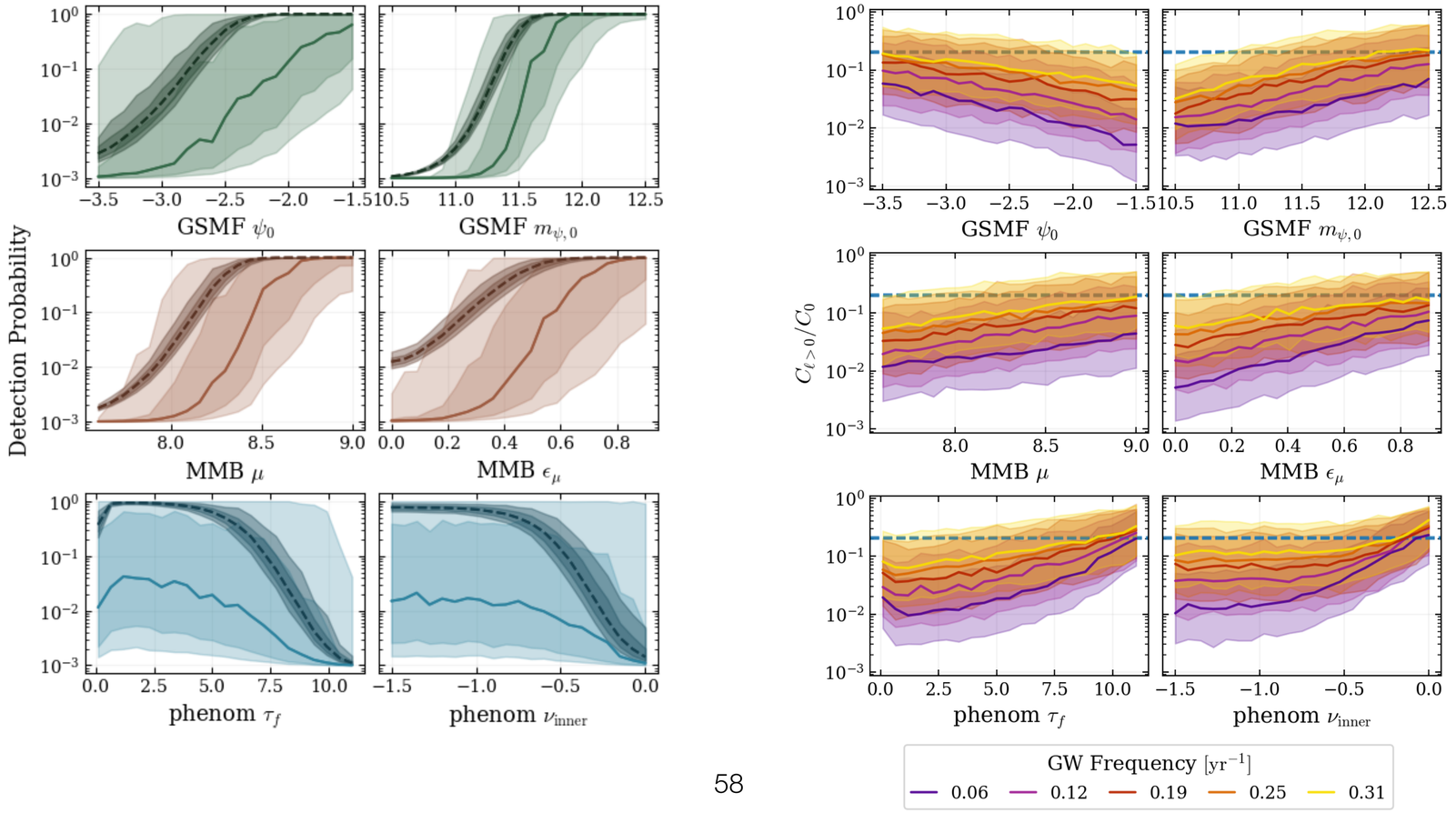

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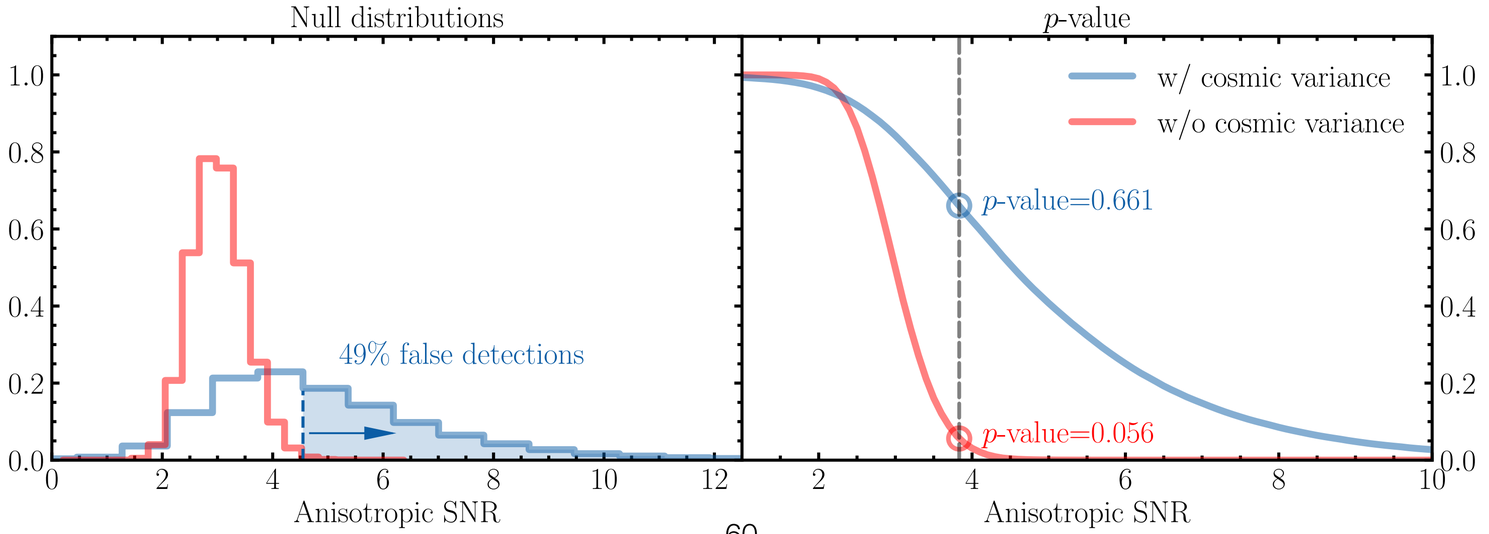

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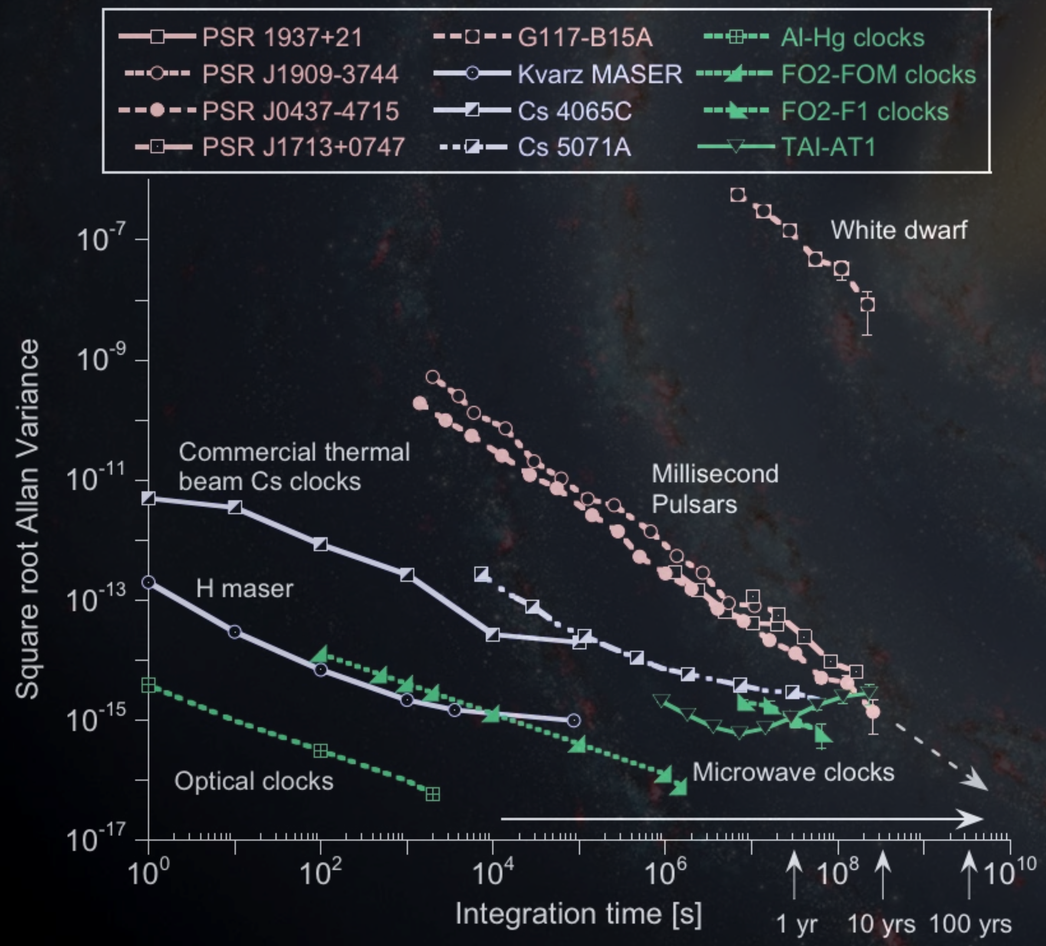
new data is coming

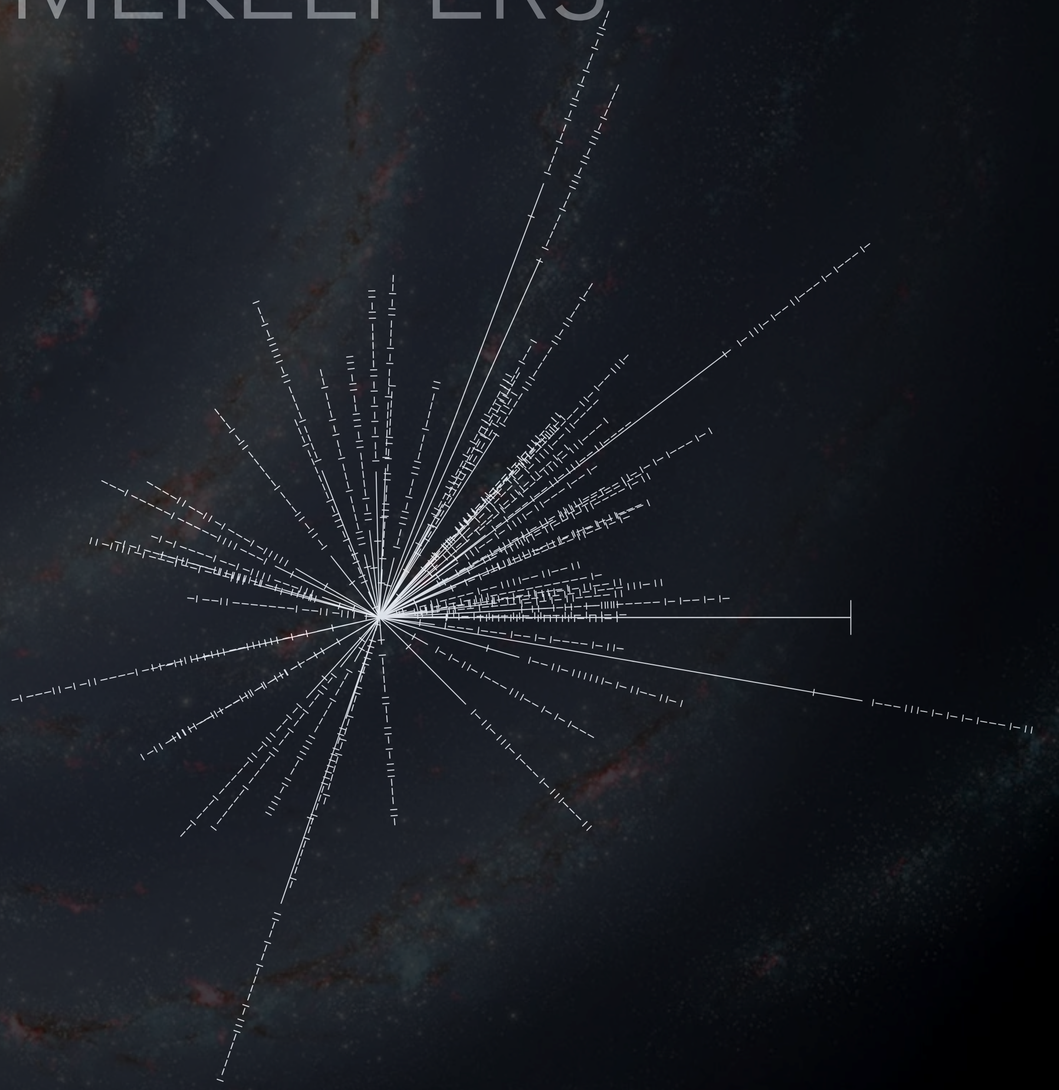
- NANOGrav 20-year data set. **Already analyzing preliminary data set.**
- IPTA DR3. **Data combination near completion.**

PTAs are not just a GW detector

A GALACTIC NETWORK OF TIMEKEEPERS

Hartnett and Luiten [1004.0115]



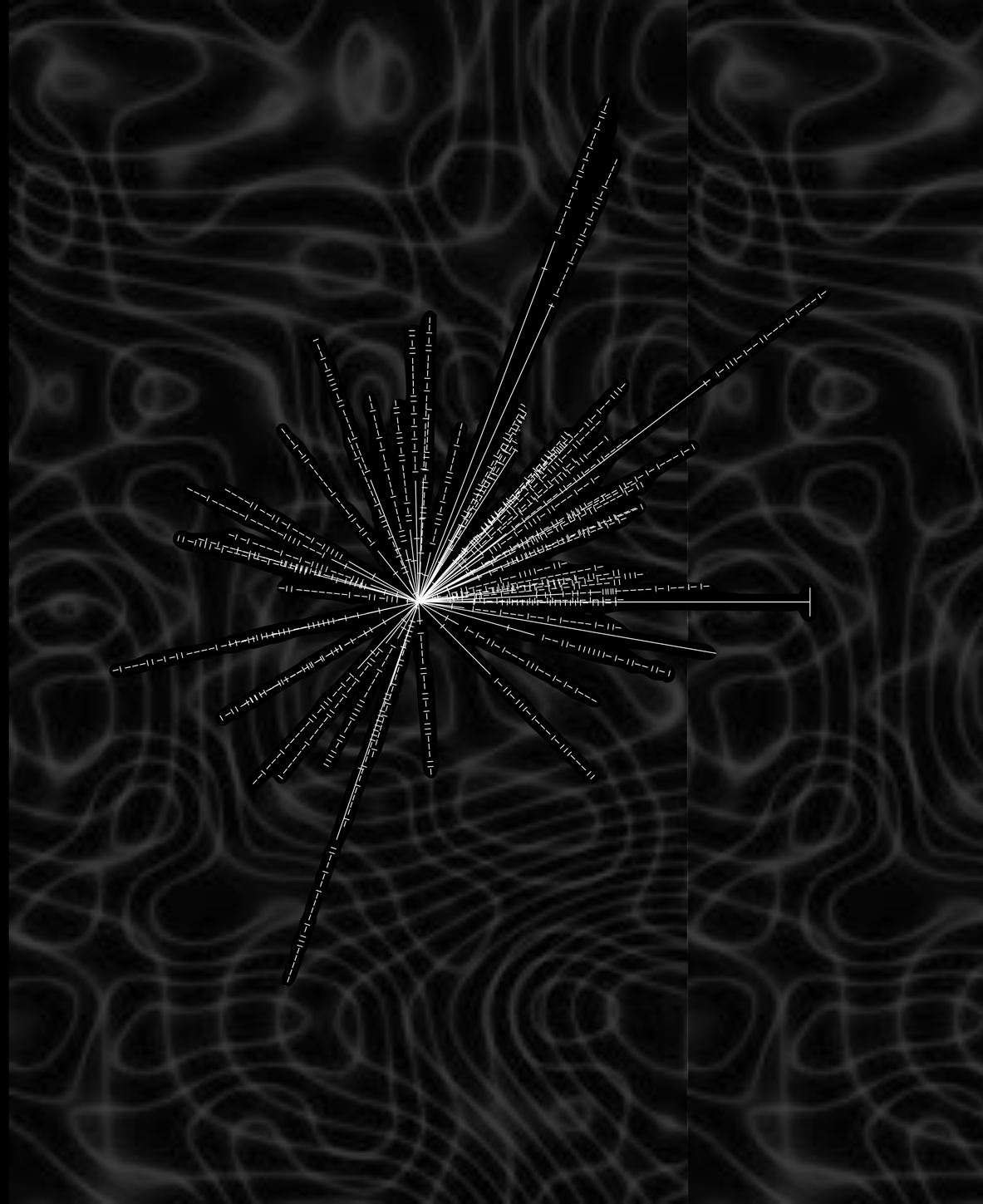


The NANOGrav 15 Year Pulsar Map

image credit: Lucas Brown (UCSC)

TESTS OF DM PROPERTIES

$$\phi(\vec{x},t) = \frac{\sqrt{2\rho_\phi}}{m_\phi}\hat{\phi}(\vec{x})\cos\left(m_\phi t + \gamma(\vec{x})\right)$$



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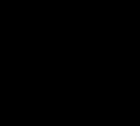
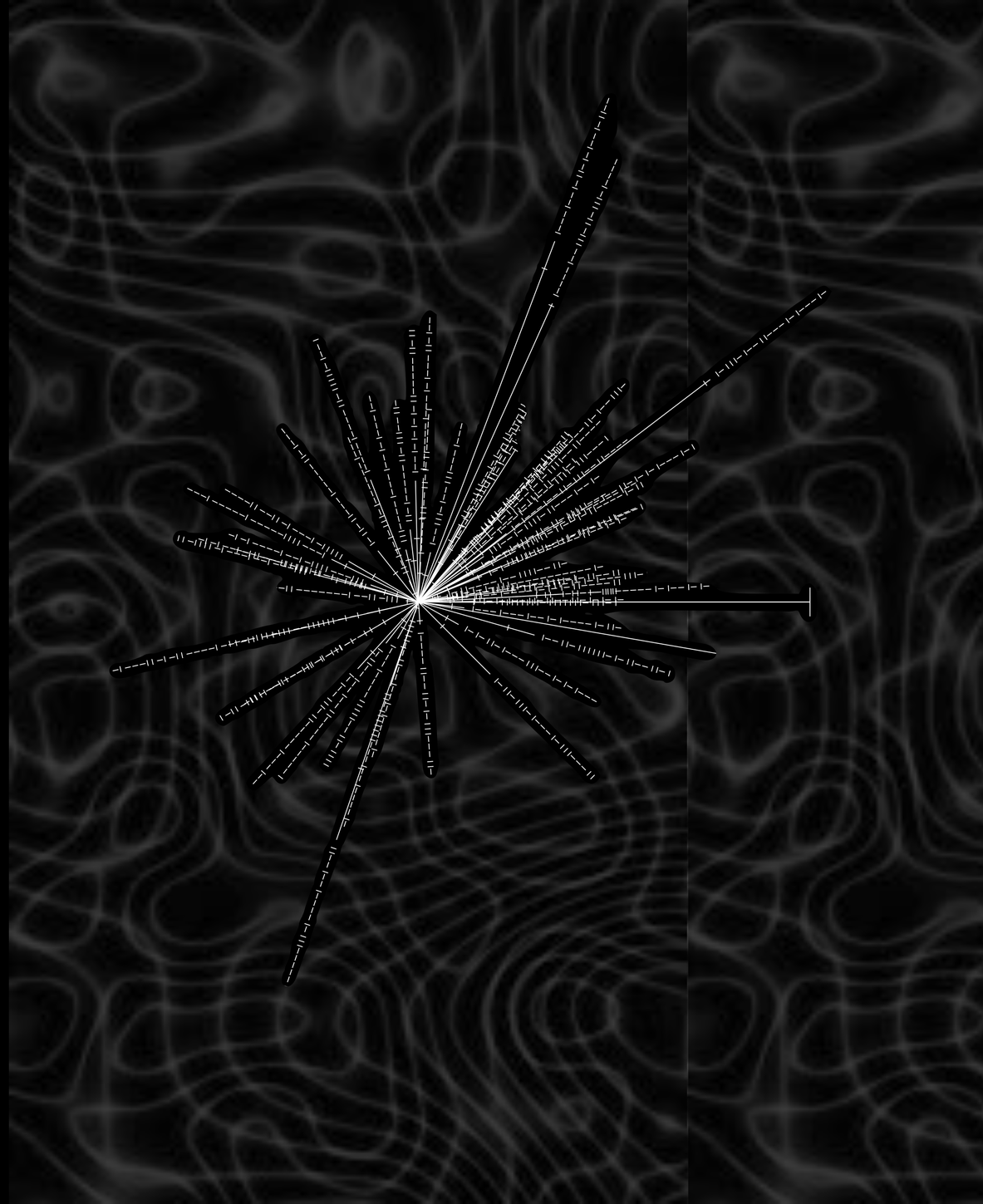


$$ds^2 = \Big[1 + 2\Phi(t,\vec{x})\Big]dt^2 - \Big[1 - 2\Psi(t,\vec{x})\Big]dx^2$$



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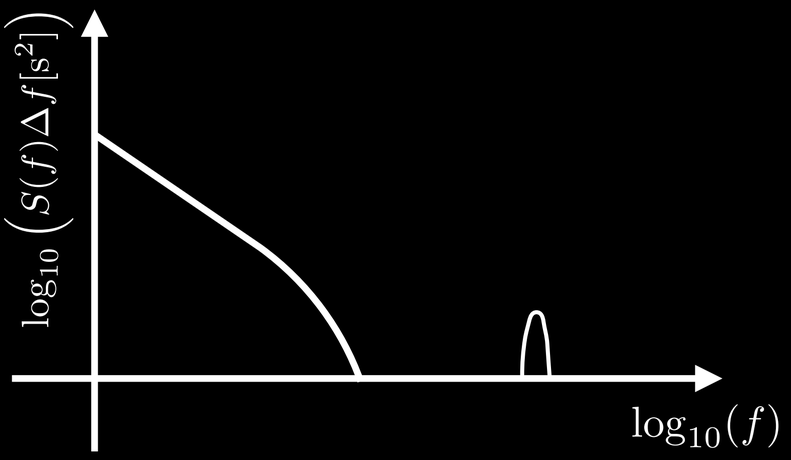
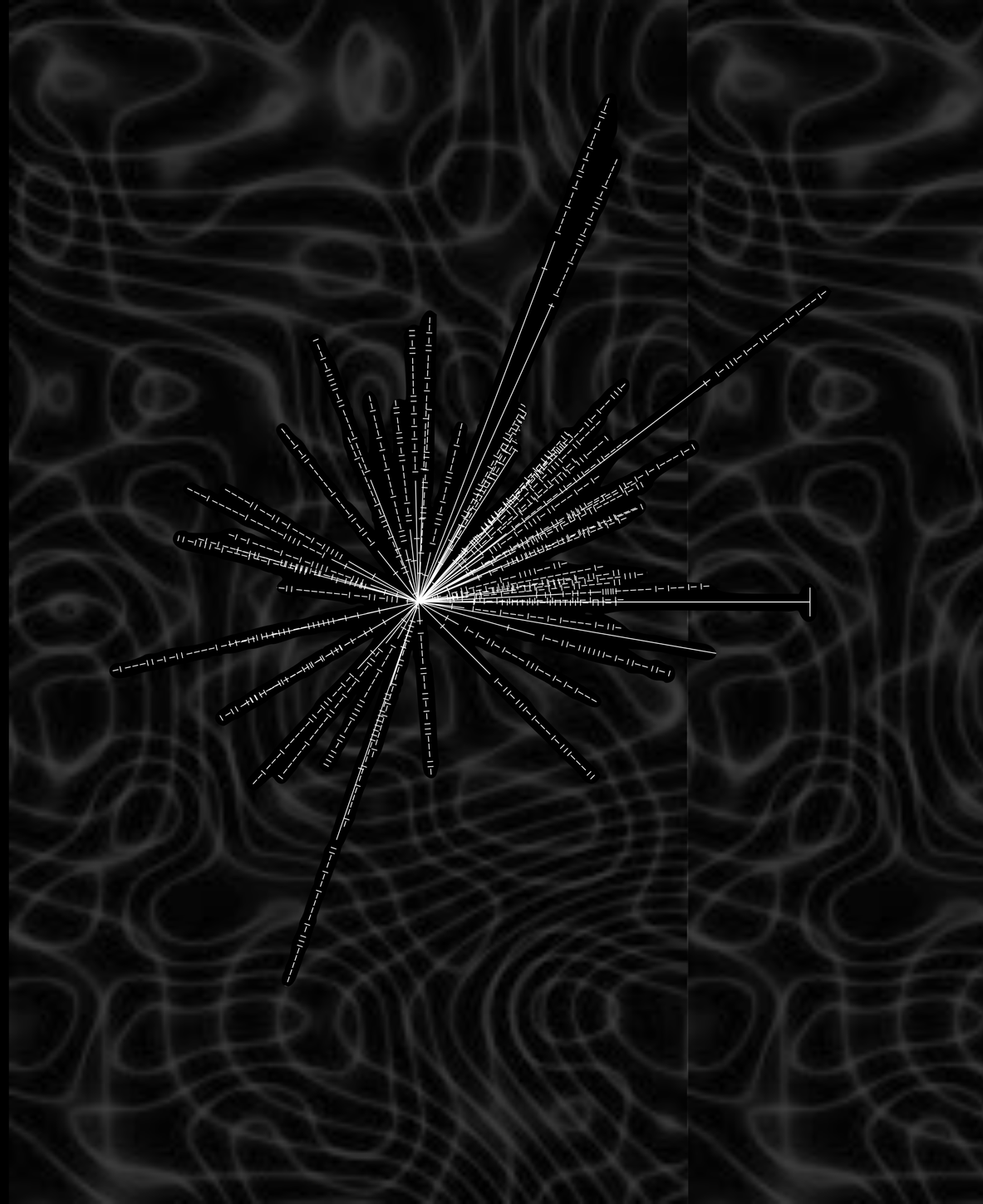


Kim, **AM**, [2312.12225]



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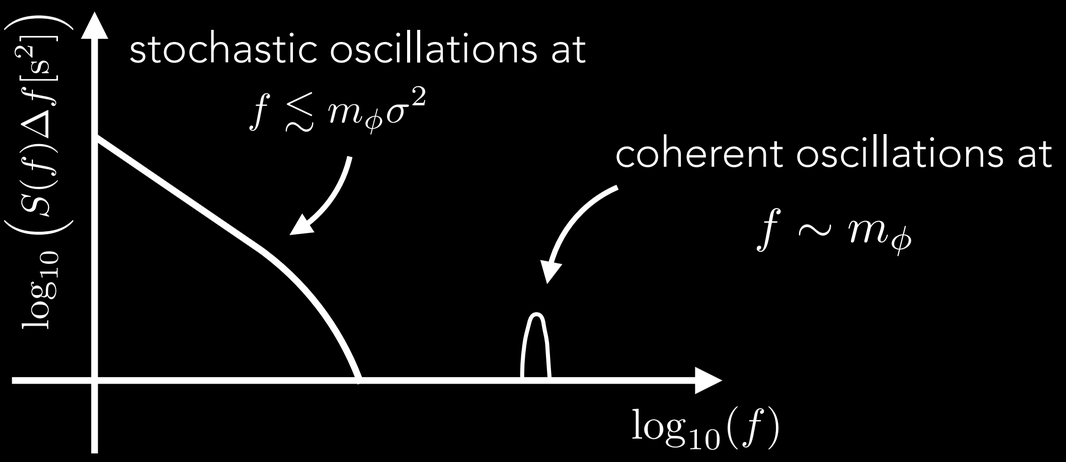
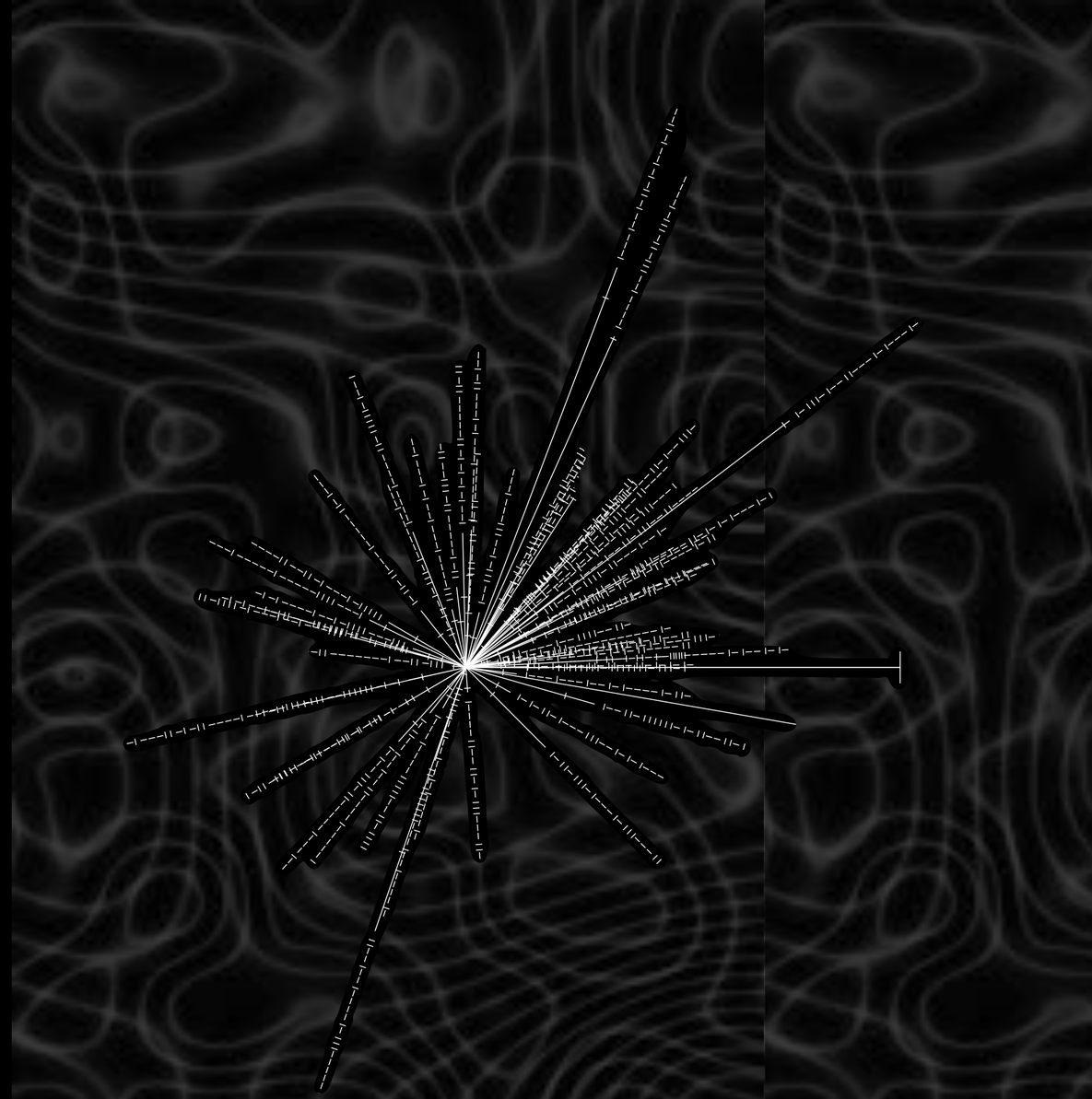
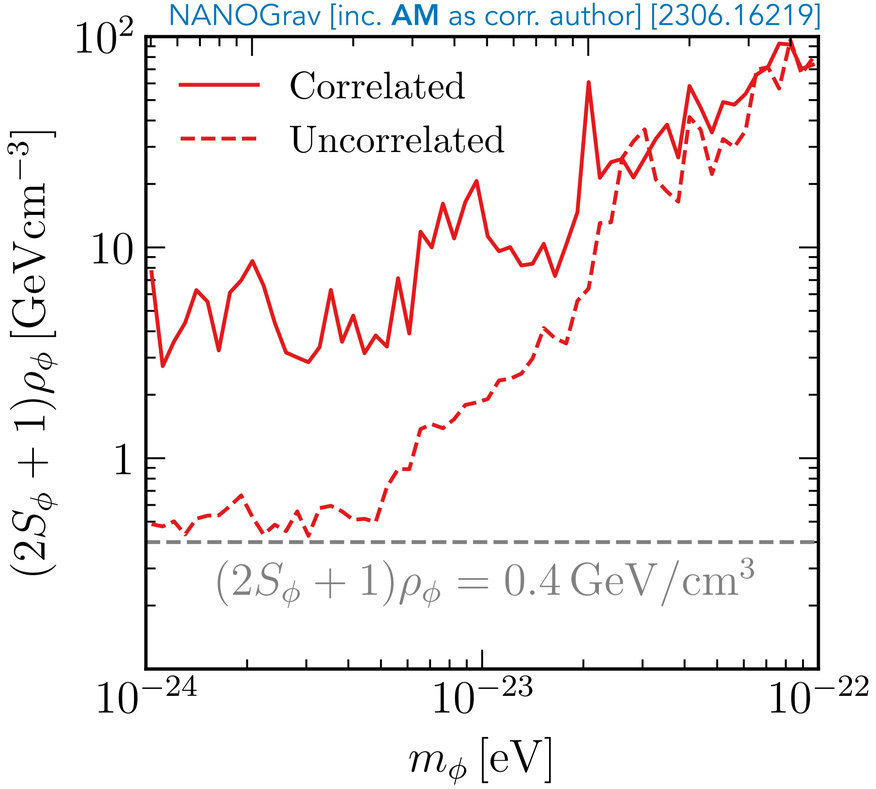




Kim, **AM**, [2312.12225]

TESTS OF DARK MATTER PROPERTIES

NANOGrav [inc. **AM** as corr. author] [2306.16219]



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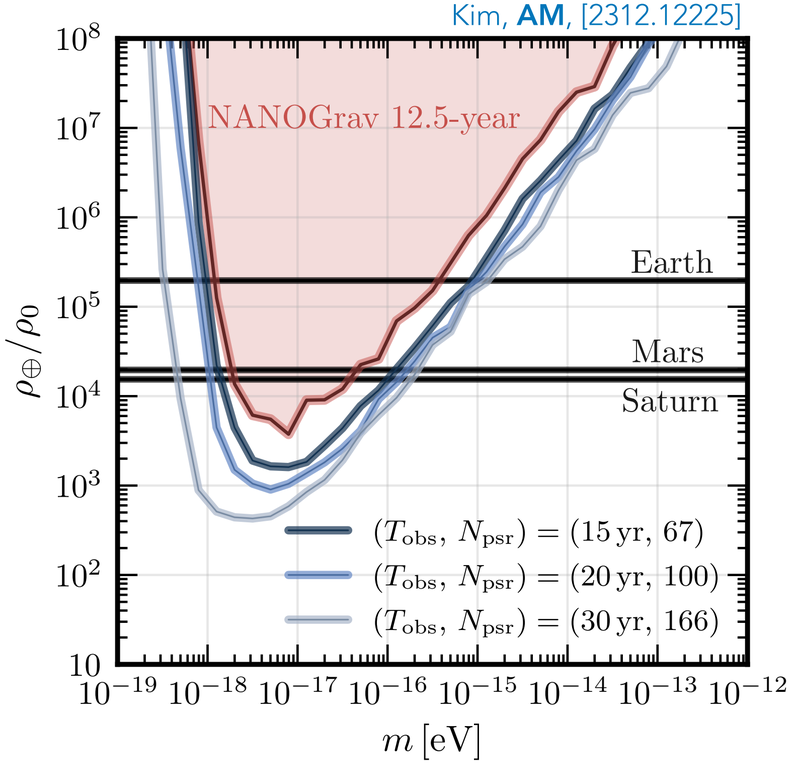
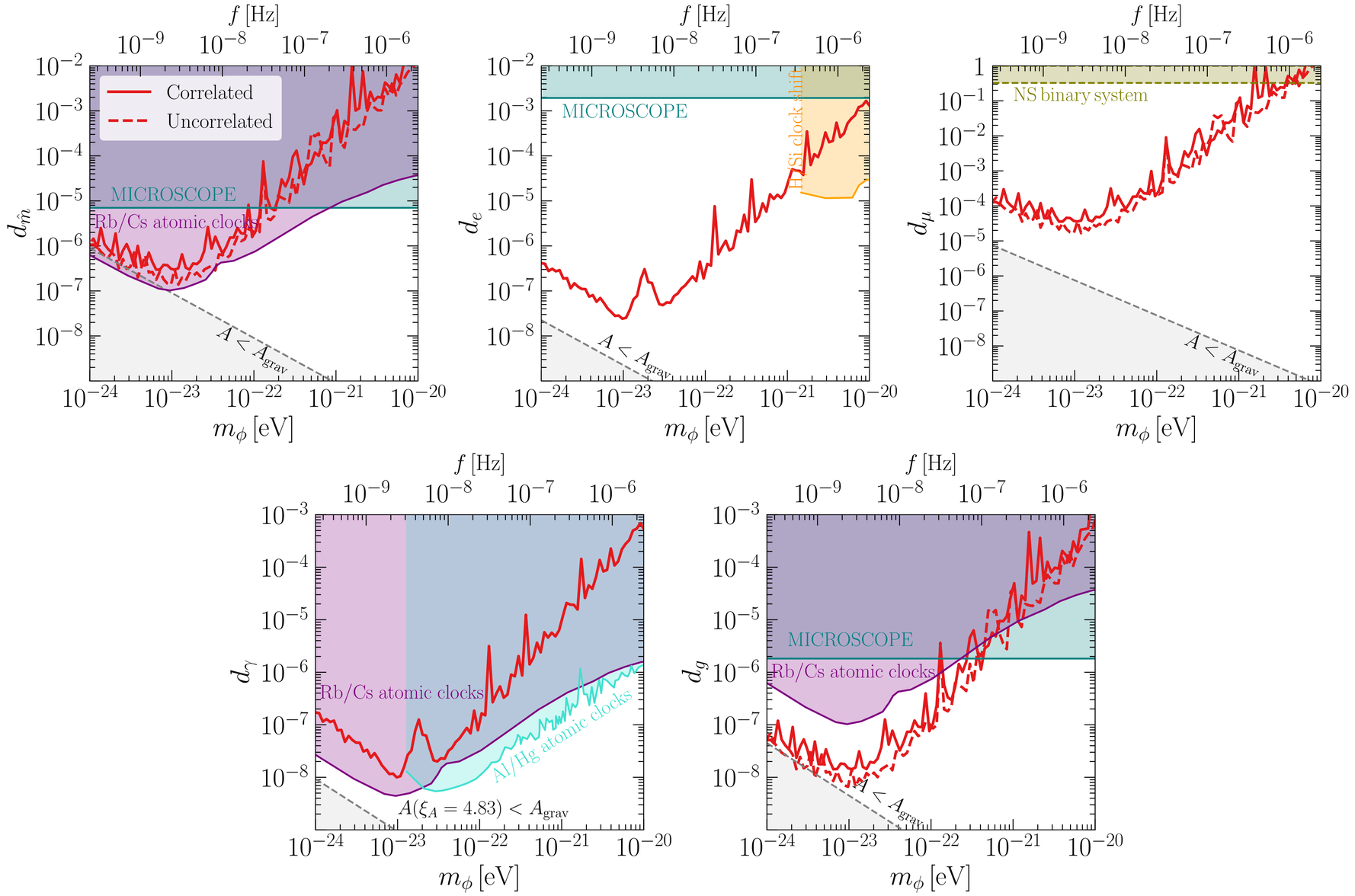


CLOCK SHIFTS



Kaplan, **AM**, Trickle, "*Constraining fundamental constant variations from ultralight dark matter with pulsar timing arrays*", PRD 106 (2022)
NANOGrav [inc. **AM** as corresponding author], "*The NANOGrav 15yr Data Set: Search for Signals from New Physics*", ApJL 951, L11 (2023).

ULDM AND MUCH MORE

testing dark matter distribution within the Milky Way

→ searches for dark matter subtrsuctures in the Milky Way

NANOGrav [inc. **AM** as corresponding author], *"The NANOGrav 15yr Data Set: Search for Signals from New Physics"*, ApJL 951, L11(2023).
Lee, **AM**, Trickle, Zurek, *"Probing Small-Scale Power Spectra with Pulsar Timing Arrays"*, *JHEP 06 (2021)*

→ searches for ULDM particles in the $10^{-16} - 10^{-14}\mathrm{eV}$ mass range

Kim, **AM**, *"Stochastic ultralight dark matter fluctuations in pulsar timing arrays"*, *PRD 109 (2024)*
Kim, Gan, **AM**, *"Probing Quadratically Coupled ULDM with PTAs"*, *in preparation*

→ ALPs searches using pulsar polarization data

Xue, **AM**, Trickle, Verma *"Pulsar Polarization Array Limits on Ultralight Axion-like Dark Matter from the NANOGrav collaboration"*, *in preparation*

tests of dark matter density profiles

→ dark matter effects on SMBHB orbital evolution

NANOGrav [inc. **AM**], *"Galaxy Tomography with the Gravitational Wave Background from Supermassive Black Hole Binaries"*, *[arXiv:2411.05906]*

tests of GR

→ constraints on the graviton mass

Cordes, **AM**, Schmitz, Schröder, Wassner *"On the overlap reduction function of pulsar timing array searches for gravitational waves in modified gravity"*, *Class. Quant. Grab. 42 (2025)*

→ searches for additional GW polarizations

NANOGrav [inc. **AM**], *"The NANOGrav 15 yr Data Set: Search for Transverse Polarization Modes in the Gravitational-wave Background"*,


strong evidence for a GWB in the nHz band

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PTAs can help us test a wide range of NP models